REINHARD & WENK

GEOLOGY OF THE COLONY OF NORTH BORNEO

52/6

GEOLOGICAL SURVEY DEPARTMENT OF THE
BRITISH TERRITORIES IN BORNEO

Bulletin No. 1

GEOLOGY

OF THE

COLONY OF NORTH BORNEO

BY

Max Reinhard, Ph.D. (Zürich), Hon. D.Sc. (Geneva)

Professor of Mineralogy and Petrology at the University of Basel

AND

Eduard Wenk, Ph.D. (Basel)

Lecturer in Petrology, Basel University

LONDON

HIS MAJESTY'S STATIONERY OFFICE

1951

Copyright Reserved

PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE

To be purchased from

York House, Kingsway, LONDON, W.C.2 429 Oxford Street, LONDON, W.1

P.O. Box 569, LONDON, S.E.1

13a Castle Street, EDINBURGH, 2 1 St. Andrew's Crescent, CARDIFF

39 King Street, MANCHESTER, 2 Tower Lane, BRISTOL, 1

2 Edmund Street, BIRMINGHAM, 3 80 Chichester Street, BELFAST

or from any Bookseller

1951

Price £2 12s. 6d. net

Copies may also be purchased from

The Geological Survey, Jesselton, North Borneo

or

The Geological Survey, Kuching, Sarawak

Printed in Great Britain under the authority of H.M. Stationery Office
by The Campfield Press, St. Albans

S.O. Code No. 88-332*

Contents

PAGE

List of Plates ... vi

List of Text Figures ... vii

List of Tables ... viii

List of Enclosures ... viii

Preface I ... ix

Preface II ... xi

Authors' Foreword ... xiii

Chapter I Physiography ... 1

Chapter II History of Geological Exploration ... 3

Chapter III Geomorphology and Quaternary Deposits ... 7

Geomorphological Problems ... 7

Quaternary Deposits ... 11

Chapter IV Outline of the Geology of North Borneo ... 11

Chapter V Tertiary Sediments and Tectonics ... 16

1. Formational Correlations and Micro-palaeontology ... 16
2. Sedimentary Record and Palaeogeography ... 19
3. Brine Springs, Mud-Volcanoes, Oil- and Gas-seepages ... 22
4. Tertiary Tectonics ... 25
5. Major Tectonic Features and Regional Relationships ... 29

Chapter VI Tertiary Igneous Rocks ... 31

A. VOLCANIC ROCKS OF SIMPORNA AREA, SE. COAST

Geology ... 31

1. Geographical and Geological Positions of Outcrops ... 31
2. Mode of Occurrence and Nature of the Volcanic Activity 31
3. Age of Volcanism ... 33

Petrology ... 35

1. Mineralogical Composition, Structure and Texture of the Dacite-Andesite-Basalt Series ... 35
2. Mineralogical Description of Tuff-Tuffite Series ... 39
3. Chemical Composition ... 41
4. Petrological Problems ... 42

PAGE

B. PLUTONIC ROCKS OF MT. KINABALU AND ASSOCIATED MINOR INTRUSIONS AND EXTRUSIONS 47

Geology 47

Petrology 51

1. Plutonic Rocks of Mt. Kinabalu proper 51

2. Minor Intrusions and Extrusions 58

3. Chemical Composition 59

CHAPTER VII PRE-TERTIARY FORMATIONS 63

A. DANAU FORMATION 63

Definition 63

Occurrence of the Danau Formation 64

The Rocks of the Danau Formation 64

The Sedimentary Rocks 64

Shales and Flysch-like Sandstones 64

Radiolarian Cherts 65

Limestones and Marls 65

The Ophiolites 66

Intrusive Rocks of the Ophiolite Series 66

Serpentines, Peridotites and Pyroxenites 66

Serpentine and Related Rocks 67

Peridotites 68

Pyroxenites 68

Gabbros 68

The Twinning Laws of the Plagioclases of Gabbroid Rocks 69

Chemical Analyses of Gabbros 69

Description of Rock Types 70

Quartz-Diorites 72

Extrusive Rocks of the Ophiolite Series 72

Diabases 73

Chemical Analyses of Diabases and a Basalt 74

Basalts 74

Spilites and Associated Rocks 75

Chemical Analyses of Spilites and Associated Rocks ... 76

Ophiolitic Breccias, Tuffs and Tuffites 77

Ophiolites versus Spilitic Suite 78

Is the Mineral Content of the Ophiolitic Rocks of North Borneo Primary Magmatic or Autometamorphic? 78

Petrochemical Characteristics of the Ophiolites 79

PAGE

Endomorphic and Exomorphic Contact-Metasomatic Alteration Products 85

Recrystallized Radiolarian Cherts and Sandstones, Chalcedonites 85

Silico-Carbonate Rocks 86

Metasomatized Ophiolites 86

Metasomatized Sediments 88

Ore-Mineralization 89

Metamorphic Ophiolites from the Contact Zone of the Kinabalu Quartz-Monzonite 90

Tectonics, Genesis and Age of the Danau Formation 91

B. SLATE FORMATION 97

C. CRYSTALLINE SCHISTS AND ASSOCIATED INTRUSIVE ROCKS 98

Preliminary Remarks 98

Age of the Crystalline Schists and Associated Intrusives ... 99

Occurrence of Crystalline Schists in the N. of North Borneo ... 99

Interior of North Borneo 100

South-Eastern Part of North Borneo 100

The Plagioclase Twins of the Crystalline Schists 104

CHAPTER VIII FINAL REMARKS AND RECOMMENDATIONS FOR FUTURE RESEARCH 105

BIBLIOGRAPHY 107

A. British North Borneo 107

B. The East Indies 108

C. General Geology and Petrology 109

D. Maps 110

E. List of unpublished Reports consulted 110

APPENDIX I LIST OF ROCK SAMPLES DEPOSITED AT THE MUSEUM OF NATURAL HISTORY, BASEL 113

APPENDIX II TABULATION OF DETERMINATIONS OF LARGER FORAMINIFERA, BY I. M. VAN DER VLERK 137

APPENDIX III MICRO-PALAEONTOLOGICAL EXAMINATION OF SOME CALCAREOUS ROCK SAMPLES FROM THE DANAU FORMATION, BY M. REICHEL ... 146

APPENDIX IV METHODS OF TOPOGRAPHICAL SURVEY 148

LOCALITY INDEX 153

GENERAL INDEX 156

List of Plates

(*Between pages 106 and 107*)

I. Tertiary fossiliferous sediments.
II. Tertiary fossiliferous andesitic tuffites (1 and 2): Tertiary volcanic rocks (3 and 4).
III. Tertiary volcanic rocks.
IV. Kinabalu intrusives.
V. Kinabalu intrusives showing transitions into microgranitic border facies.
VI. Danau Formation: sediments.
VII. Danau Formation: sediments and contact-metasomatic rocks.
VIII. Danau Formation: intrusive ophiolites.
IX. Danau Formation: intrusive ophiolites.
X. Danau Formation: ophiolites and associated rocks.
XI. Danau Formation: extrusive ophiolites.
XII. Danau Formation: extrusive ophiolites.
XIII. Danau Formation: extrusive ophiolites and their tuffs.
XIV. Crystalline schists.
XV. Crystalline schists.
XVI. Gunong Kinabalu (quartz-monzonitic intrusive body).
XVII. River scenery.
XVIII. Fossil ripples (1): mud-volcano (2): scenery (3 and 4).
XIX. Sandstone (1): mud-volcano (2 and 3): gas-seep (4).
XX. Gunong Rara.

List of Text Figures

		PAGE
1.	Orographical sketch map of North Borneo	8
2.	Morphological history of the Tambalunan-Sarudong Valley	10
3.	Cross-sections through the area SE. and SW. of Marudu Bay	26
4.	Section along the NE. coast of North Borneo	27
5.	Section along Tg. Lokpadsang, W. coast of the Kudat Peninsula	27
6.	Photogeological map of the synclinal basin of S.Malua (Kinabatangan) ...	28
7.	Photogeological map of the synclinal basin of S.Bangan (Kinabatangan) ...	29
8.	Mineralogical composition and specific gravity of the Tertiary volcanic rocks ...	36
9.	Variation diagram of the Tertiary volcanic rocks	40
10.	Relation between normative and modal anorthite content in the volcanic rocks from the E. coast of North Borneo	46
11.	Sketch of Mt. Kinabalu, seen from SW.	48
12.	Schematic section across the Tertiary intrusion of Gunong Kinabalu	48
13.	The mineral succession in the quartz-monzonitic rocks of Mt. Kinabalu ...	52
14.	Mg-Ca-Fe diagram of the Tertiary igneous rocks of Mt. Kinabalu	60
15.	Variation diagram of the Tertiary igneous rocks of Mt. Kinabalu	60
16.	Mg-k diagram of the Tertiary igneous rocks of North Borneo	61
17.	Or-Ab-An diagram of the Tertiary igneous rocks of North Borneo	61
18.	Q-L-M diagram of Tertiary and pre-Tertiary igneous rocks of North Borneo ...	61
19.	Diagram showing relations between the normative anorthite content and the coefficient α of saturation with silica	62
20.	Section through P. Burong N. of Klias Peninsula	66
21.	Variation diagram of the ophiolitic suite of the Danau Formation	80
22.	Alk-si diagram of Indonesian ophiolitic and dioritic rocks	82
23.	Mg-k diagram of the ophiolitic suite of the Danau Formation	83
24.	Q-L-M diagram of the ophiolitic suite of the Danau Formation	83
25.	Q-L-M diagram of the ophiolitic rock suite of the Talaud Islands	83
26.	Or-Ab-An diagram of the ophiolitic suite of the Danau Formation	84
27.	Mg-Ca-Fe diagram of the ophiolitic suite of the Danau Formation	84
28.	Schematic stratigraphical column, southern part of Kudat Peninsula	93
29.	Sketch of Gg. Tambuku, seen from P. Sebatik	93

List of Tables

		PAGE
I.	Stratigraphical correlation table. Northern and eastern North Borneo	*facing* 16
II.	Stratigraphical correlation table. Western, southern and south-eastern parts of North Borneo	*facing* 17
III.	Analyses of crude-oils	25
IV.	Chemical analyses of Tertiary igneous rocks	44
V.	Molecular base and Niggli values of Tertiary igneous rocks	45
VI.	Percentage weights and Niggli values of Kinabalu hornblende and related types	56
VII.	Frequency distribution of plagioclase twins in gabbros	70
VIII.	Chemical analyses of pre-Tertiary rocks	*facing* 80
IX.	Molecular base and Niggli values of pre-Tertiary rocks	*facing* 81
X.	Frequency distribution of plagioclase twins in crystalline schists	104
XI.	North Borneo astro-fixes	151

List of Enclosures

(*In pocket at end*)

I. Geological map of North Borneo, scale 1:500,000.

II. Structural map of North Borneo and adjacent Philippine Islands, scale 1:2,500,000.

III. Geological sketch-map of Balambangan, Banggi and Manawali Islands, scale 1:100,000.

IV. Geological map of the northern part of the Kudat Peninsula, scale 1:100,000.

V. Geological sketch-map. SE. coast of Marudu Bay, scale 1:100,000.

VI. Geological map of Kinabalu area, scale 1:100,000.

VII. Geological sketch-map of the middle course of the Milian (Kinabatangan) River and its tributaries, scale 1:200,000.

VIII. Geological sketch-map of the middle course of the Segama River and the Darvel Bay region, scale 1:100,000.

IX. Geological sketch-map of the region W. of Darvel Bay, scale 1:100,000.

X. Geological sketch-map of Blantian Valley, scale approx. 1:100,000.

Preface

by the DIRECTOR OF COLONIAL GEOLOGICAL SURVEYS

DURING the year 1948 the Shell Oil Company informed the Colonial Office that it had arranged with Professor Reinhard and Dr. Wenk to compile a comprehensive Report on the Geology of North Borneo based on all known sources, published and unpublished, and that it would be willing to hand the work to the Government of North Borneo for publication. The Governor of North Borneo was glad to accept this generous offer, and the Shell Company then expressed its willingness to agree to a suggestion that the Report might be published as Bulletin No. 1 of the newly-created Geological Survey Department of the British Territories in Borneo. On behalf of that Department I wish to thank the Shell Company for its timely assistance in presenting this Report.

Special thanks are due to the authors, Professor Reinhard and Dr. Wenk, who have devoted so much of their knowledge, time and energies to the complex task of co-ordinating their own results with those of all the other workers named in their Foreword and in the text.

The Shell Company has not only furnished the very large sum of money necessary for pursuing, over many years, the geological and geophysical investigations that have supplied much of the material used by the authors, but it has also employed many of the staff of its associated Company at The Hague, The Bataafsche Petroleum Maatschappij, in translating the script from the German in which the greater part was written, and in preparing for publication all the text-figures, tables, plates and geological maps prepared by the authors and other geologists which add so greatly to the value of the bulletin. Furthermore, it has very considerably reduced the cost of publication borne by the Government of North Borneo by printing at The Hague the three coloured maps (Enclosures I, II and VI). I gratefully acknowledge this valuable service, rendered specially by the Shell Company's Chief Geologist at The Hague, Dr. H. M. E. Schürmann, and his staff, which has so greatly facilitated the task of the Directorate of Colonial Geological Surveys in seeing the work through the press on behalf of the Government of North Borneo.

All of the field-work on which this account is based was completed before the year 1942, in the period when the Colony of North Borneo went by the name of British North Borneo, or more shortly, B.N.B. The old name is used in the author's Foreword and in some parts of the text.

In conclusion, I wish to express my appreciation of the high standard of the completed work, which will serve as a well-laid foundation on which to build the future activities of the new Geological Survey of the British Territories in Borneo.

F. DIXEY.

London,
December, 1949

Preface

THE extension of the Shell Group's exploration into North Borneo was a natural sequel to the establishment of successful oil fields in Sarawak and Brunei (Sarawak Oilfields Ltd., and The British Malayan Petroleum Co., Ltd.).

In 1934 the Anglo-Saxon Petroleum Co., Ltd., a Shell Group company, was granted a concession by The British North Borneo Company, and geological exploration was started with the assistance of Sarawak Oilfields Ltd. in October, 1934, and has continued since with the addition of aerial photogeological and geophysical surveys and core-drilling. In 1938 the Anglo-Saxon assigned its interest in the concession to the Shell Company of British North Borneo Ltd.

As the preliminary reconnaissance surveys drew to a close it became evident that while large tracts of country traversed by the survey parties were of little or no interest from the standpoint of oil possibilities, much interesting information had been gained of the geology of North Borneo in general.

Data obtained from these surveys revealed facts which throw light on the geological history and structure of Borneo and fill numerous gaps in the still incomplete geological picture of the most interesting region comprising the East Indies as a whole.

During their quest for oil, the geologists often crossed areas of igneous and metamorphic rocks, from which they took numerous samples, and it became apparent that a systematic study of these collections would be of value to the country, particularly in so far as such an investigation might assist in the search for mineral deposits of economic importance and in the classification of soil-types for agricultural and arboricultural purposes.

In 1938 Shell offered to supply this information in a form suitable for publication to The British North Borneo Company. This offer was accepted and Shell's technical and scientific advisers in The Hague (the Bataafsche Petroleum Maatschappij) put in hand the compilation of a report. Dr. H. M. E. Schürmann, Chief Geologist of the Royal Dutch/Shell, realizing the importance of the igneous rocks and mineralization possibilities, took advantage of the Shell Group's world-wide contacts in questions of research to ask Professor Reinhard, Director of the Mineralogical and Petrographic Institute at Basel, if he would undertake the task of examining the rock collections and, with the aid of Shell's information and maps, write a book on the " Geology of British North Borneo ", which would be placed at the disposal of the authorities for publication by them.

Professor Reinhard, who had himself once explored in North Borneo, took as his collaborator in the research and compilation of this work his colleague Dr. Wenk, Lecturer in Petrology at Basel University and one-time geologist with Shell, who had been assigned during the years 1936 to 1939 to oil exploration survey in this territory.

To gain as complete a record as possible of all geological surveys which had been carried out in North Borneo, the Nederlandsche Koloniale Petroleum Maatschappij was approached on the subject of the publication of this volume and they very kindly agreed to allow Dr. Hotz to co-operate with the authors.

It is hoped that this book will serve a useful purpose as a foundation upon which the newly-formed Geological Survey of North Borneo may base future research.

The Shell Company of British North Borneo Ltd. take this opportunity of expressing their appreciation of the decision of the Directorate of Colonial Geological Surveys to publish this monograph.

SHELL COMPANY OF BRITISH NORTH BORNEO LTD.

London,
December, 1949

Authors' Foreword

THIS volume contains a compilation of the geological exploration work carried out in British North Borneo as well as the results of some years research on the numerous samples collected by geologists of the Royal Dutch/Shell and the Nederlandsche Koloniale Petroleum Maatschappij, including those assembled by the authors themselves.

The work of individual geologists and research workers is acknowledged in the text.

Work carried out in Basel included the examination of over a thousand samples collected by the geologists Hotz, Jezler, Niethammer, Pannekoek van Rheden, Reinhard, Spiegelhalter and Stamm. The Shell samples examined are those of Leicester and Wenk.

To the 227 rock-slides already in existence 546 new thin-sections were added, and, in addition to the seven rock-analyses already carried out, a further 26 rocks and two rock-forming minerals were chemically analysed at Basel.

The petrographic and petrochemical investigations were divided as follows: Prof. Reinhard examined the samples of the Danau and Slate Formations as well as those of the crystalline schists, while Dr. Wenk studied the Tertiary igneous rocks, the Kinabalu intrusives and the Simporna volcanics. Dr. Grütter analysed the plagioclases of the Danau Formation and of the crystalline schists on the Fedoroff universal-stage. He also established the quantitative modal mineral composition of the analysed ophiolites and diorites on the integration-stage in as far as they admitted of measurement.

Various analysts were entrusted with the task of making the chemical analyses; their names are mentioned at the foot of each analysis.

All investigations were carried out in the Mineralogical and Petrographic Institute of Basel University, where the necessary thin-sections were prepared by the most capable slide-makers, Mr. E. Glauser and the late Mr. K. Wahl.

The text of this volume is mainly the work of Prof. M. Reinhard and Dr. E. Wenk. The greater part was written in German and has been translated by members of the staff of the Bataafsche Petroleum Maatschappij (B.P.M.), the head subsidiary of the Royal Dutch/Shell, situated in The Hague.

Chapters I, II, III, V and VI were written by Dr. Wenk, Chapter VII by Prof. Reinhard and Chapters IV and VIII jointly by the two authors.

Chapter III contains a short contribution by Dr. H. Boissevain, and the palaeontological part of Chapter V was written by Dr. J. Dufour. Chapter VII includes a section by Dr. Wenk on the petrochemical characteristics of the ophiolites.

Appendix I was drawn up jointly by the two authors. Appendix II was compiled by the B.P.M. Geological Department at The Hague, Appendix III was written by Prof. M. Reichel of the University of Basel, and Appendix IV was produced by the Topographical Department of the B.P.M. at The Hague.

The geological map, Enclosure I, has been drawn at The Hague office of the B.P.M., and is based on the surveys of the geologists whose names are mentioned in Chapter II, and revised and expanded by the two authors.

Distribution charts showing the sample localities of the rock and fossil collections of Drs. W. Hotz and G. Niethammer were prepared by the late Dr. A. Tobler, and have been of inestimable service in the preparation of this volume.

The text figures were drawn up by the following geologists: Figs. 1, 8–19, 21, 22 by Dr. Wenk, Figs. 2, 6 and 7 by Dr. Boissevain, Figs. 3 (part) and 20 by Dr. Hotz, Figs. 3 (part), 5 and 28 by Dr. Niethammer, Fig. 29 by Prof. Reinhard and Fig. 4 by Drs. Schneeberger and Wenk; and were afterwards redrafted in the B.P.M. office at The Hague.

All the micro-photographs of Plates I–XV were taken by Dr. Wenk in the Mineralogical and Petrographic Institute at Basel, and he also contributed the landscape photographs of Plates XVI–XIX. The aerial photograph, Plate XX, was commissioned by the Royal Dutch/Shell.

The geologists who worked in B.N.B., most, if not all, of whom learned to love this peaceful, friendly land of dense primeval forest, mangrove swamps, rapids and " totem and taboo ", were greatly indebted to the officers of the Chartered Company of British North Borneo for their every assistance, and the completion of their work was only made possible by the help of the ever friendly and willing Dayaks, Dusuns, Muruts and others who accompanied the geologists on their expeditions, often not without some danger to themselves. The Dayaks, who had migrated from Sarawak to various parts of B.N.B. to collect *damar puteh* (natural resin), and the Dusuns from the River Kuamut proved to be the most able guides, particularly on account of their experience in negotiating the numerous and dangerous rapids encountered in the upper reaches of the rivers.

The authors wish to acknowledge their indebtedness to the Royal Dutch/Shell, and especially to their Chief Geologist, Dr. H. M. E. Schürmann, for their assistance in preparing this treatise for publication.

Finally, to all who have assisted in the production of this volume the authors extend their heartfelt thanks.

M. REINHARD
E. WENK

Basel University,
November, 1949

N.B. The authors have throughout followed the Continental practice of referring to the optical directions X, Y and Z as n_α, n_β and n_γ.

CHAPTER I

Physiography

THE Colony of North Borneo, with an area of approximately 30,000 square miles, forms the northernmost part of the island of Borneo and includes also several minor islands. The mainland of North Borneo extends from the most southerly point, the head-waters of the Padas River in latitude 3° 42′N. to the northern tip of the Kudat Peninsula 7° 02′N., and from longitude 115° 20′E. to 119° 16′E. It lies entirely in the tropics.

The shape of North Borneo is commonly and aptly compared with the profile of an eastward-facing hog's head. Its coastline, in contrast with the remainder of Borneo, is very broken and embraces a number of excellent natural harbours. The most prominent features of the coast are, in the south-west, the Klias Peninsula between Brunei and Kimanis Bay, where a low range of hills is separated from the mainland by extensive and deep swamps, and in the north the Kudat and Bengkoka peninsulas enclosing Marudu Bay, which is sheltered on the north by the adjacent islands of Balambangan, Banggi and Manawali. Along the north-east coast lie Paitan, Labuk and Sandakan bays, the last two separated by Sandakan Peninsula, where Sandakan, the pre-war capital of British North Borneo, is situated. South-east from Sandakan lie the Dent and Simporna peninsulas, with Darvel Bay and Cowie Harbour. The total length of the coastline is almost 1,500 km.

The land is bounded on the west by the relatively shallow South China Sea, on the north-east by the Sulu Sea, a large and deep basin characterized by a comparatively flat and horizontal floor at a depth of about 3,000–4,000 m. and by steep sides, and on the south-east by the Celebes Sea, with similar depth and configuration. Between the South China and the Sulu Seas, and between the Sulu and Celebes Seas, island arcs lie along morphological lines joining the most northerly and easterly points of North Borneo with the Philippine Islands.

North Borneo is a sparsely-populated country of rolling, jungle-clad hills and mountains. The chief orographical feature in the territory is Kinabalu Mountain, over 4,100 m. high (13,455 ft.). Apart from this isolated mountain massif, the country consists mainly of mountains from 500–2,000 m. in height rising somewhat sharply from low hilly ground. Most of the mountain ranges are not very well defined either in height or form. They make up rather irregular masses of high land, much dissected and with occasional peaks which tower above the surrounding country. Only the Crocker Range, parallel to the west coast, forms a fairly continuous range which might be considered the backbone of the country. The general direction of the mountain ranges is NE.–SW., but, as pointed out above, the ranges are rarely regular and continuous. The series of strips of aerial photographs taken in the southern and eastern parts of the country show up rather clearly the very irregular topography of these parts of North Borneo. Several of the features indicated on the British North Borneo Government 8 miles to 1 in. topographical map of 1934 appear to be rather misleading, especially the long continuous mountain ranges.

The hills reach down to the coast in many places, especially in the west and south-east. Along the north-east coast vast alluvial flats exist. These coastal plains generally pass into swamp near the coast. Sometimes there is no intervening coastal plain and the hills cease abruptly at the swamps.

A special feature of the inland topography of North Borneo is the occurrence of some broad dissected peneplains, 500–600 m. high, on the principal watershed between the rivers draining into the South China Sea and those flowing into the Sulu Sea. These peneplains appear as a pronounced depression to the east of the Crocker Range and Mt. Kinabalu, and stretch from the Suk-Labau area (watershed between the Padas and Kinabatangan) in a northerly direction via the Tambunan plain (570 m.), Pegalan valley to the head-waters of S.Labuk (Ranau plain, 500 m.) and S.Sugut and reach as far as the Bengkoka Peninsula, where they possibly continue beneath

the Tertiary e_5 sediments. Toward the east the Suk-Labau plains follow the Kinabatangan-Labuk watershed and, to the south, the Suk-Penawan (Talangkai) divide. A high plain separates also S.Kuamut (Kinabatangan, Sulu Sea) from S.Sibuda and Sapulut (Sembakong, Celebes Sea). These peneplains might prove of great importance in the planning of overland routes in North Borneo.

The appended 1:500,000 map (Enclosure I) gives a clear picture of the drainage system. The main watershed between the China and the Sulu-Celebes Seas runs nearer the west than the east coast. Consequently, all the large rivers drain to the east, with the exception of the Padas which, flowing north of the North Borneo-Sarawak-Netherlands Borneo boundary, joins the south-flowing Pegalan near Tenom and then cuts through the Harewood-Crocker Range to drain into Brunei Bay. As mentioned above, this main watershed is, apart from the Kinabalu-Trusmadi area, formed by hilly plains rather than by mountain ranges. A secondary watershed, dividing the rivers flowing into the Sulu Sea (Kinabatangan, Segama) from those draining into the Celebes Sea (Sarudong, Kalabakang, Blantian, Klumpang), rises above a peneplained country and comprises some of the wildest and most inaccessible mountain masses in Borneo.

The greater part of North Borneo is covered with virgin jungle. Secondary growth forest, grassland (lalang, *Imperata exaltata* Brogn.), resulting from the pernicious system of shifting cultivation, and agricultural land occur in the comparatively well-populated west coast districts, and also form small strips along the more important rivers.

Owing to the favoured geographical position of the country and its good natural harbours, the coasts of North Borneo are easily reached from Singapore, Hong Kong and Manila. But travel within the country is not easy; the interior especially is still hard of access. There is a railway line, 125 miles long, leading from Jesselton along the south-west coast to Beaufort, following the Padas River as far as Tenom-Melalap. Strangely enough, this railway existed before any roads were made. Up to this day there are no overland routes in North Borneo. Only in the neighbourhood of Jesselton, Kudat, Sandakan, Lahad Datu and Tawau, and between Melalap and Keningau are there roads, but these are not linked together. Though the country is badly served in this respect, it possesses over 500 miles of bridle-paths, which are to be found chiefly on the west coast and in the south-western interior.

In the eastern and central portion of the country the great rivers Sugut, Labuk, Kinabatangan and Segama form the highways. At certain water levels these rivers are navigable for launches as far as the first rapids. Their head-waters and tributaries are accessible by outboard motorboat, but are chiefly reached by dugout. The geologists exploring the country mainly follow the rivers, because in a tropical country rock exposures are to be found almost exclusively along watercourses. River journeys offer splendid scenery (see Plates XVII and XVIII), but the traveller is largely dependent on the level of the rivers.

Floods (*banjir*) render river journeys very dangerous, particularly if they start as suddenly as is occasionally experienced, when the level of the streams rises several metres in a few hours. Since these *banjir* generally commence at night-time, they are a special menace to the traveller camping on a river bank. After heavy thunderstorms even the main rivers may become impracticable owing to the strong current, innumerable whirlpools and masses of floating logs which are swept along. Many rivers of North Borneo, such as the S.Kuamut, the most important tributary of the Kinabatangan, are notorious for their large and numerous *giram* and *wossoi*, as the turbulent rapids and waterfalls in solid rock are called (see Plate XVII). These obstacles render up-stream journeys very tiresome, but there is no more thrilling experience in Borneo than shooting the rapids on the way down-stream. When crossing the watersheds or exploring low undulating areas one may follow one of the many elephant tracks or cut a jungle trail (*rentis*), which is usually overgrown again in a few weeks.

The climate of North Borneo is comparatively healthy for a tropical country. There are no extremes of heat. The temperature in places near the coast varies from an average minimum of 23°C. to an average maximum of 31°C. (73° and 88°F. respectively). In the uplands and in the jungle the morning temperatures are lower. The mean annual rainfall amounts to roughly 2·5 m. (approx. 100 in.). The heaviest rains fall during the north-east monsoon, which usually begins in November and lasts until March. December and January are the wettest months and during this period travelling is not advisable. Throughout the year there is no dry season, but in the central and eastern parts of the country the period of the

south-west monsoon, which usually begins in July and lasts until October, is drier than the rest of the year.

According to the 1931 census North Borneo had only 270,223 inhabitants. The two largest native tribes are the Dusun and the Murut, names which cover a number of pagan groups. The Dusun occupy the comparatively well-populated west coast districts and the plains in the north-eastern areas; the Murut the remote uplands in the south-western interior of the country. The coastal villages are inhabited chiefly by Malays, Bajaus, Suluks and Chinese, the last forming the main commercial and industrial population of the towns. Only 362 European residents were recorded in 1931.

Several of the oil geologists' reports give good and detailed accounts of means of access, inhabitants, labour and living conditions in limited parts of North Borneo, but it has not been thought necessary to include such information here. Readers interested in the general geography of the country are referred to the " Handbook of the State of British North Borneo ", issued by the British North Borneo (Chartered) Company (1921), and to the excellent book " British North Borneo ", by Owen Rutter (1922).

CHAPTER II

History of Geological Exploration

MANY explorers have already traversed North Borneo. Several of these concerned themselves with exploitable mineral deposits, but only a few were scientists who contributed to the geological knowledge of the country by publishing the results of their work. In most cases the articles appeared in professional periodicals which are difficult of access. The bibliography accompanying this paper is intended to include all geological publications of importance.

First of all we would refer to two books dealing with the history of the geological exploration of North Borneo. A detailed account of the journeys made by early explorers and an outline of the geological knowledge of the island of Borneo as known at that time was published by Posewitz (1889, 1892). This geologist had travelled through parts of Netherlands Borneo, but had never set foot on the territory of British North Borneo. He had, however, collected the literature on North Borneo which was available at that time and compiled a geological map. We would refer to this publication only in connection with the early, rather unsystematic, period of exploration and not to the geological part of it, which naturally is now obsolete.

O. Rutter (1922) described the journeys made by some mineral prospectors in his interesting account of British North Borneo, but did not mention the actual geological explorers of the country.

The fact that a North Borneo Geological Survey Department has not until recently been founded accounts for the somewhat peculiar and unfamiliar exploration history of the country and is also responsible for the very inadequate geological knowledge of that region. The actual geological exploration of the country was not carried out by the Government as in other overseas territories as, for instance, in the Philippines, Malaya and the Netherlands East Indies, but almost exclusively by geologists employed by private companies who had secured prospecting concessions in North Borneo. Only a small portion of the results obtained by these geologists has been published. Most of the unpublished reports and geological maps, however, were at the disposal of the compilers of this paper and were utilized by them (see list of reports, p. 110).

Some unpublished official reports of the British North Borneo Company from the years 1880–1904, dealing with mineral research in North Borneo, are listed in the bibliography given by O. Rutter (1922) and W. J. Worth (1940). These old reports have not been consulted by the present authors as they are only of historical value. Short accounts of exploration campaigns have also appeared occasionally in the British North Borneo " Herald ".

Our present geological knowledge of North Borneo, therefore, is almost exclusively based on the findings of the field geologists of the oil

companies and on the palaeontological and petrographical examination of their rock samples. Unfortunately the many prospectors for ore and coal deposits have contributed very little to our knowledge. It is particularly regrettable that the journeys and explorations in the Segama River area which were undertaken by several parties of gold prospectors during the period from 1883–1904, in some cases at considerable expense, did not yield any geological results with regard to this highly interesting river system, in fact, did not even supply an answer to the question of the origin of the placer gold. Consequently our knowledge of this river area, consisting chiefly of crystalline rocks, is based on data obtained by oil geologists and on the laboratory examination of their rock samples.

The first reliable geological data on North Borneo are due to Frank Hatton (1885), a young energetic chemist who was engaged as a mineral explorer in 1881 by the Chartered Company of North Borneo. Hatton travelled through the area between the River Labuk and Marudu Bay, through the Kudat Peninsula and from the mouth of the Kinabatangan as far as the head-waters of the River Pinanga. On an expedition in the Segama area this intrepid explorer met his tragic death in a hunting accident after only eighteen months of activity.

In 1899 C. Schmidt, an expert of international repute in questions relating to oil geology and Professor of Geology at Basel University, visited Labuan and the adjacent coast of the Klias Peninsula, Padas Bay and Brunei. In his report, of which a condensed abstract was published in 1901, he referred to several oil-seepages and recommended a thorough survey of the area concerned, especially of the Miri and the Baram rivers. Schmidt was the first experienced geologist who set foot on North Borneo soil. His recommendations subsequently proved of great importance to the geological exploration of the country. Later (1904) he published some of his observations made in 1899. A geological map and sections are attached to his publication on the geology of North-West Borneo and on the new island which had formed there.

In 1905 the British Borneo Exploration Company was founded, which acquired for a period of 50 years the right to exploit all mineral resources in North Borneo with the exception of the coal deposits in the south-eastern part of the country. The founding of this company was connected with the discovery of the occurrence of manganese ore in the Marudu Bay area (Dieseldorff, 1906), which later, however, was found to be of no economic value (Pilz, 1916). From the geological point of view the only important and valuable document relating to the exploration carried out on behalf of this company is the publication by R. Pilz (1913) on the geology of British North Borneo. During the period 1909–1911 Pilz, on behalf of the British Borneo Exploration Company, examined all the ore deposits known at that time as well as various coal deposits, and conducted five large expeditions. On two occasions, proceeding from Marudu Bay, he traversed the Sugut-Labuk area in the direction of Sandakan; on one journey he crossed the northernmost part of the country from west to east, while on two other journeys he visited the south-eastern and the south-western coastal districts respectively. He also explored the western part of the Kinabalu massif. His observations are reliable and his geological sketch map of the country gives, for the first time, a fairly good idea of the distribution of the various formations. The British Borneo Exploration Company was disbanded in 1913, since none of their work showed economic results.

Already in 1908 the Borneo Exploration Company had transferred their concession rights for petroleum prospecting to a subsidiary company, the British Borneo Petroleum Syndicate Ltd. (B.B.P.S.). On behalf of this company, and in accordance with the recommendations made by Schmidt—as far as can be gathered from the records—the northern part of the Klias Peninsula was geologically explored in 1909 by J. J. Pannekoek van Rheden, after prospecting work had already been carried out by I. A. Stigand. Pannekoek van Rheden also visited the Kudat and the Sandakan Peninsulas in the same year and confirmed the existence of a few oil indications. From April 1910, to April, 1911, the Klias Peninsula area was explored in more detail and geologically mapped by G. Niethammer, who was followed for a short time by W. Bernoulli. In the period from February to June, 1911, the B.B.P.S. carried out deep drilling in the Mensian River area (Klias Peninsula), during which gas and traces of heavy oil were found. I. A Stigand, who at that time had also traversed the south-eastern coastal area on behalf of the same company, published in 1911 a physiographic-hydrographic study containing occasional geological observations.

In the year 1912–1913 the Boundary Commission

carried out an expedition along the border region between Netherlands Borneo and the State of British North Borneo and located the boundary line between these two areas (report published in Dutch: Verslag, 1913). The participation of the mining engineer W. D. Munniks de Jongh (1913) in this expedition and the report published by him, have contributed to some degree to the geological knowledge of North Borneo, in spite of the fact that Munniks de Jongh explored almost exclusively the Netherlands area and crossed the frontier only along the Sibuda and Sedalir rivers.

Prospecting for oil in North Borneo was again continued by the Nederlandsche Koloniale Petroleum Maatschappij (N.K.P.M.) since 1912. This Company arranged for the detailed and large-scale geological exploration of the country by the employment of a larger staff of experienced geologists.

The whole north-western part of North Borneo (north-west of the line S.*Sugut-Paranchangan-Trusmadi Mountains-S.Suk-Tenom-Brunei Bay) was geologically explored by G. Niethammer and W. Hotz and their assistants E. Hartmann and J. Zurkirch during the period 1913–1915. W. Hotz also surveyed Banggi and Balambangan Islands; he crossed North Borneo from the west coast via Keningau-Pinanga-Kinabatangan as far as the north-east coast near Sandakan and ascended, *inter alia*, Mt. Kinabalu. The south-eastern part of the country, particularly the Sarudong-Kalabakang area, and the Simporna and Dent Peninsulas, was explored by M. Reinhard and his assistants K. Stamm, F. Spiegelhalter and H. Jezler during the period 1913–1914. M. Reinhard himself surveyed the Sarudong, Kalabakang, Blantian and Klumpang area, and made also a cursory trip up the Kinabatangan River as far as Pinanga. The Tawau-Simporna region was explored by Spiegelhalter, and the Segama and Darvel Bay region by Stamm and Jezler. Moreover, Stamm reconnoitred the area around Sandakan Bay and Jezler the Labuk river system.

These geologists did not merely make sporadic observations along widely-spaced routes like former explorers, or more detailed examinations of locally confined and isolated outcrops, but they also thoroughly explored the region by covering it with a narrow-meshed network of traverses. We are indebted to them for a large number of detailed geological maps and copious material in the form of rock samples and fossils. The collections of rock samples made by Hotz, Niethammer, Reinhard and their assistants, containing 993 specimens, as well as those of Pannekoek van Rheden, with copies of their maps and reports, were deposited in the Basel Museum of Natural History.

These geologists were not only the first to carry out a systematic geological exploration of North Borneo, but in the course of their journeys they also drew up the first detailed topographical maps covering large areas of the country itself. Their excellent topographical sketches, checked by many cross-connections, were utilized in compiling the official map of North Borneo (1934).

Some results obtained during this geological reconnaissance, carried out on behalf of the N.K.P.M. during the period 1913–1915, have been recorded in the following publications:

The rock samples of the private collection of K. Stamm were examined by J. Wanner and H. Bücking and the results published by Wanner (1921), together with the geological observations made by Stamm. This paper and the many accompanying geological sketch maps give a wealth of information. It is without doubt the most important contribution to the geological knowledge of a limited region of North Borneo that has been published. Stamm was a reliable observer and the value of the paper has been greatly enhanced by the compiler Wanner, who is a well-known authority on East Indian geology. Bücking was certainly not, and his description of the rock samples of igneous origin has contributed little to the value of the paper. Through the courtesy of Prof. R. Hocart of the University of Strasbourg, where the material studied by Bücking is deposited, M. Reinhard was able to examine the thin sections and to revise Bücking's determinations.

A paper by H. Gerth (1923) deals with the anthozoan fauna of the younger Tertiary (collections Niethammer and Reinhard), another by J. Felix (1921) with the same group of fossils collected by Stamm.

M. Reinhard (1924) published a survey of the physiography and geology of the south-eastern part of North Borneo. The accompanying map gives for the first time an insight into the topography and geology of this hitherto unknown country. From Reinhard's and Spiegelhalter's collections A. Borloz (1924) examined some andesitic rock samples from the Simporna Peninsula. L. Rutten (1915, 1921, 1925 a, b) reported in

*The letter " S " in close juxtaposition to a place name signifies the Malay " sungei ", meaning " river ". For further Malay abbreviations see head of Appendix I, p. 113.

several publications on the palaeontological examination of samples of foraminiferal limestones collected by Hotz, Niethammer and Pannekoek van Rheden and also on the geological results obtained by these explorers. In his well-known lectures on the Geology of the Netherlands East Indies (Rutten, 1927), he gave also a brief outline of the history of the geological exploration of North Borneo. Moreover, this publication offers the most comprehensive and best documented survey of the geology of the entire East Indian Archipelago. M. G. Rutten (1948) published a short note on the foraminifera of a limestone collected by Niethammer.

The collections made by Hotz, Niethammer, Pannekoek van Rheden, Reinhard, Spiegelhalter and Stamm were studied petrographically by M. Reinhard and E. Wenk and the fossiliferous sediments were palaeontologically examined by I. M. van der Vlerk and M. Reichel, and the results incorporated in the present paper. Unfortunately the rock samples collected by Jezler in the Labuk area were lost on their way to Europe during the first world war. Therefore our information of this important pre-Tertiary area is limited to the few observations reported by Jezler, who was the only geologist who explored that region.

From a scientific point of view, the geological exploration carried out on behalf of the N.K.P.M. in North Borneo yielded very fruitful results, but no results whatever were obtained from the economic point of view. Four wells in the proven oil-bearing area of the Klias Peninsula were drilled to depths of 572 m. (Well I), 390 m. (II), 897 m. (III) and 727 m. (IV). They did not, however, yield sufficient production, as the pronounced tectonic disturbances had adversely affected the accumulations of oil. Two wells on the small island of Mangalum, off the west coast, had to be abandoned at shallow depth (440 m. and 354 m.) on account of technical difficulties. The locations of these wells are indicated on the geological map 1:500,000 (Enclosure I).

In 1913 the British portion of the island of Sebatik was examined on behalf of the Royal Dutch/Shell Group by M. Blumenthal and an exploration deep well was drilled, which met only traces of oil.

During the first world war the Japanese Kuhara Mining Company prospected for oil in North Borneo, but nothing is known of the geological results obtained. H. Yabe (1918) examined palaeontologically the limestone from the Batu Tumanggong (lower course of the Kinabatangan River) collected by one of the Japanese geologists.

At Sequati (Kudat Peninsula) an exploration well, over 600 m. deep, was drilled in 1921 by the Kuhara Mining Co. without finding oil in paying quantity. In 1920 the D'Arcy Exploration Company, a subsidiary of the Anglo-Persian Oil Company, prospected the Klias Peninsula but decided not to drill, and between 1924 and 1931 a syndicate of Singapore Chinese carried on desultory operations there.

While the first systematic regional geological exploration of North Borneo was carried out by geologists on behalf of the N.K.P.M., the second large-scale exploration campaign was conducted during the period 1935–1939 by geologists employed by the Royal Dutch/Shell Group. When planning this new prospecting campaign it was not considered necessary to have new exploration work carried out in the western and south-eastern part of the country, which had already been subjected to a reliable and thorough examination by Hotz, Niethammer and Reinhard during the period 1913–1915. Published geological maps of these regions were, in fact, available (Wanner, 1921, Reinhard, 1924, Rutten, 1925, 1927), which showed that they were of little interest from the point of view of an oil company. The Shell Company of British North Borneo therefore concentrated their exploratory efforts in the practically unknown north-eastern part of the country and particularly the Dent Peninsula. Moreover, the central part of the country was cursorily explored. The following geologists carried out this work:

W. F. Schneeberger geologically examined the extensive coastal area between the Kudat and the Sandakan Peninsulas during the period 1935–1936. J. Irving surveyed the south-western part of the country and some of the islands off the north coast in 1935 and P. Leicester explored the Lahad Datu-Segama area in 1936. In the same year J. Ph. Roothaan and E. Wenk mapped the central and upper part of the Kinabatangan river area, including its major tributaries. Wenk subsequently traversed the southern central part of the country from east to west along the Kinabatangan-Pinanga-Sapulut-Talangkai-Pensiangan-Keningau route, and in the ensuing period 1937–1939 surveyed the lower Kinabatangan area, and more particularly the eastern part of the Dent Peninsula. In 1937 he ascended Mt. Kinabalu and in 1938 carried out a rapid reconnaissance of the south-eastern interior part of North Borneo to establish the stratigraphic

correlations while traversing this region by the Tawau - Kalabakang - Tiagau - Kuamut - Kinabatangan-Sandakan route. Parts of the Dent Peninsula were geologically examined in detail by H. Parsons and G. Sung in 1938 and by P. von Schumacher in 1939, while H. Parsons also subjected the west coast island of Mangalum to a detailed examination in 1939. The object of this subsurface work was to test the subsoil of the practically unexplored and marshy coastal regions by means of test-pitting, hand-augering and core-drilling. This work was discontinued in October, 1939, on account of the outbreak of war, and was resumed in 1948.

The rock samples collected during the expeditions of 1935 to 1939 must be considered as lost, with the exception of 116 samples of igneous rocks from Mt. Kinabalu and the Tungku area of the Dent Peninsula collected by Wenk, 21 samples of crystalline schists and volcanic rocks from the Segama area collected by Leicester and a collection of mollusca from S.Togopi (Dent Peninsula) described by L. R. Cox (1948). These rock samples were also petrographically examined by Reinhard and Wenk for the purpose of this paper.

The regional geological exploration of the entire Sibuku and Sembakong river area in Netherlands Borneo from the east coast as far as the Sarawak frontier, carried out on behalf of the Royal Dutch/Shell Group by W. F. Schneeberger and R. Bächlin during the period 1939–1940, has considerably enriched our geological knowledge of the southern part of North Borneo. These geologists extended their exploration into the Sibuda and Sembakong-Lagungan area to include British territory, so as to link up with the above-mentioned survey of central British North Borneo.

The fact that the prime object of most of these explorations was the search for oil has tended to restrict field studies to those formations which appear to be most intimately connected with the presence of oil. For this reason the areas built up by igneous and metamorphic rocks and by pre-Tertiary sediments have received but little attention. Nevertheless, some problems concerning the Tertiary igneous and pre-Tertiary formations have advanced sufficiently to be discussed on a scientific basis. This is mainly due to the initiative of the petrologists among the geologists engaged in the search for oil and to the detailed petrographical and petrochemical examination of the rock samples collected. The igneous areas deserve attention not only from a purely scientific point of view, but are also of great interest to the mineral explorer and the soil scientist. It is hoped that this publication and outline of our present knowledge will be an incentive to other geologists to investigate further the problems which have presented themselves but have not yet been solved.

This treatise will demonstrate that our knowledge of the geology of North Borneo is still far from complete on account of the large extent of the area still unexamined, and its purpose is rather to pass on to future explorers and to scientists interested in the geology of the East Indian Archipelago the information so far acquired. The detailed catalogue of rock samples, the fossil lists and the detailed maps should prove particularly useful for this purpose.

CHAPTER III

Geomorphology and Quaternary Deposits

Geomorphological problems

A STUDENT of morphology would find North Borneo a most interesting country. A few significant facts and stimulating problems have come to light, but the inaccessibility of the country, the lack of adequate maps and perhaps chiefly the fact that the traveller in the jungle of Borneo rarely gets a view of the country to be explored, render morphological studies very difficult. A systematic treatment of these problems is therefore not yet possible. The following points relating to geomorphology struck the geologists exploring the country:

Eccentric position of the dominant mountains and ranges with respect to the drainage system and apparent independence of prominent orography and

Fig. 1. Orographical sketch map of North Borneo

main watersheds. The rough sketch map (Fig. 1) shows the facts better than any verbal description. Often the main watersheds are surprisingly low, while high mountains separate the tributaries of one and the same river system. This is the case in the Labuk region, where the Mentapok-Pomuntangan-Meliau Mountains, between the middle course of the Labuk and its tributaries Liwagu Kuananan and Tungud, reach a height of 1,300 m., while in the head-waters the watershed Labuk-Sugut reaches only 585 m. (Bt. Pau) between S.Liwagu Kuananan and S.Merali (Sugut), and 650 m. (Bt. Bagahunan) between S.Liwagu Kuananan and S.Lohan (Sugut). South-east of the Mentapok Mountains the watershed between the Labuk and the Karamuak-Kinabatangan rivers rises only 70 m. above the two rivers. Good examples of the eccentric position of the dominant mountains are to be found also in the Kinabatangan area, the most important drainage system in North Borneo. Here high mountains, such as Gg. Rara (more than 1,500 m., see Plate XX), SSW. of Tangkulap, Bt. Kiniau (about 1,200 m.), ESE. of Pinanga, Batu Tulis and Batu Timbang (Kuamut), with its edible bird's-nest caves, Gg. Dinokat, famous for its white *damar*,* and said at one time to have been fitted in the Bornean way with bamboo and *rotan*† ladders to make its summit more easily accessible,‡ rise within the triangle formed by the Milian and its tributaries Kuamut and Pinanga. On the main watershed of the Kinabatangan drainage system, however, such elevations are entirely missing. In fact it is possible to cross from the east to the west coast of North Borneo, for instance, by the Kinabatangan-Labau-Suk-Padas route, without climbing higher than 450 m. above sea-level. This

*Natural resin.

†Rattan.

‡The sheer rock walls of Gg. Dinokat are clearly seen on aerial photographs.

native track does not follow a pronounced morphological depression in the form of a pass, but a dissected peneplained country. These features are in striking contrast to Alpine morphology, where the dominant mountain massifs (Mont Blanc, Mts. Rosa, Finsteraarhorn, Bernina) occupy the watersheds between the great European rivers and the passes are pronounced depressions. In North Borneo the features discussed appear to be due to the facts that the prominent orography is in close correlation with the geological structure, some resistant rock bodies having an eccentric position, and that relics of Tertiary and Quaternary erosion plains, which bequeathed the present drainage system, form part of the present relief in the interior.

Close correlation between geology and orography

Owing to their comparatively young age and strong resistance to erosional forces, bodies of Tertiary igneous rocks form some isolated mountain peaks. The best example is Mt. Kinabalu (4,100 m.), which is a plutonic body composed of quartz-monzonite. A similar intrusion of granodiorite in Tertiary strata forms the unexplored Gunong Rara, SSW. of Tangkulap (Milian). This remarkable mountain, which shows up well on the aerial photographs (see Plate XX), has a perfect elliptical shape and the summit seems to tower at least 1,500 m. above the adjacent valleys. It cannot be identified with any peak shown on the Government map. The nature of the rock became evident from boulders found in S.Sinoa. The Tertiary volcanic rocks on the south-east coast also form high mountains, such as Mt. Magdalena (1,350 m.).

Uplifts of the pre-Tertiary Danau Formation and of the older crystalline schists offer some of the wildest mountain massifs of the country, and their highly dissected and rugged relief without any persistent ridges shows up very characteristically on the aerial photographs (e.g. mountains between between S.Segama and the tributaries Malua and Kuamut of the Kinabatangan River).

Areas of sandstones of Palaeogene and Lower Neogene Age seldom show a pronounced relief, except for the Crocker Range parallel to the west coast. These series were peneplained in late Tertiary times.

Regions of alternating Miocene sandstones and shales, however, are characterized by pronounced relief with distinct slopes and scarps, often forming high ranges of hills, especially in the Milian-Kuamut-Pinanga of the interior and Kalabakang-Sarudong-Tambalunan areas in the south-eastern part of North Borneo, near the Dutch boundary. These Miocene uplands were not worn down in Tertiary times.

Tertiary erosion plains as an integral part of the present relief

The northern part of the Bengkoka Peninsula has the nature of a slightly elevated plateau, and on field geological evidence it is regarded as the remains of a peneplained surface of late Te age. Similar features have been observed in other parts of North Borneo. The importance of Tertiary erosion plains as an integral part of the present relief is clearly demonstrated by aerial photography. For instance, the late Te plain of unconformity has been laid bare around the Tangkulap synclinal basin (see Enclosure VII and Fig. 7). Again, the surface between the Kalabakang shales and the unconformably overlying Kapilit sandstones in Kalabakang Valley still appears as an element of the present relief. The watershed between S.Tiagau-Kalabakang and S.Bayudon-Kuamut, where relics of the conglomerate overlying this unconformity occur, is a pronounced depression (360 m.), with mountains built of younger formations rising at its side. Old dissected peneplains are of common occurrence in North Borneo. Various observers have noted, from a study of different parts of the Lagungan-Sembakong drainage system in the southern central part of North Borneo, that this area appears to be a dissected peneplain. The aerial photographs of this Pensiangan-Sapulut area show hills of low to medium height minutely dissected by erosion. The well preserved plains occurring on the principal watershed between the rivers draining into the South China Sea and those mentioned above flowing into the Sulu Sea, also appear to be related to Tertiary (late Te) erosion plains.

River capture

Some of the alluvial plains in the south-western interior to the country, especially those in the Kamabong-Tenom-Keningau area, appear to be of lacustrine origin. Terraces and lacustrine beds have been observed in several places, and on the aerial photographs low, flat, mesa-like features can be traced near Kamabong on the Padas, which most probably form part of old lake beds. It seems likely that an ancient lake existed in this part and was tapped and drained by the Padas through retrogressive erosion through the Crocker

Range at the present Padas gorge. The series of fluviatile conglomerates (up to 700 m. thick), found on the Klias Peninsula, may be related to this event. This geological argument supports native tales of a lake at Tenom and of a rock, Batu Penotal, at the head of the Padas gorge, which had been kicked away by a giant, thus allowing the waters to rush through the Padas gorge. Before cutting through this gorge, the waters of the Padas-Pegalan-Suk river system probably which formed a rock-barrier more resistant to erosion. Meanwhile the original Sarudong, flowing in softer rocks at a much lower erosional level than the Luis-Giram Besar River, captured this river laterally at two points successively along a strongly fractured zone. The powerful retrogressive erosion, starting from the elbow of capture and deepening the valley up-stream, must have caused both a reversal of flow in the Giram Besar and a direct connection of the Tambalunan with the Sarudong.

Fig. 2. The Morphological History of the Tambalunan-Sarudong Valley
Photogeological interpretation by H. Boissevain

flowed in a north-easterly direction (Tambunan-Ranau-NE. coast). Other river captures in the SE. part of the country have been described by Reinhard (1924, p. 123).

Interpretation of aerial photographs by Boissevain (see Fig. 2), has made it quite evident that Reinhard was right in stating that the Z-shaped bend where the Tambalunan is connected with the Sarudong via the Giram Besar was the site of a capture. Boissevain describes this capture as follows:

" Originally the Tambalunan must have followed the subsequent valley of the Upper Tambalunan-Ngklanjau-Siglayan cut into soft shales. The Luis-Giram Besar River was its normal affluent. When lowering its bed, in the area of the present Ngklanjau, the river reached the Kapilit sandstone, So a water divide between the Ngklanjau and the Siglayan came into existence on the barrier of the harder rock.

Study of the aerial photographs clearly shows that captures and sub-recent changes of river courses have occurred also in the Segama region. These changes appear to be the real cause of the failure of the gold prospectors in that area. The present river system misled the explorers of the alluvial gold deposits and prevented the location of the source beds. The watershed between the lower Kinabatangan River and Sandakan Bay is formed locally by freshwater swamps and is so ill-pronounced that it is reasonable to relate the vast coastal swamps S. and SE. of Sandakan Harbour to an earlier course of the Kinabatangan River."

Positive and negative movements

Along parts of the north-east coast, especially around Marudu Bay, Dewhurst Bay and the Dent and Simporna Peninsulas, there are definite signs, such as raised beaches, terraces and reefs, which point to a sub-recent emergence of the land. In the Cowie Harbour region, however, according to Stigand (1911) the deltas have been formed under the influence of secular depression. The many *giram* or rapids in solid rock, along the whole course of the Sarudong-Tambalunan River and those of the Upper Kalabakang River and their tributaries, together with the lack of gravel terraces along these rivers, are proofs of the action of great erosional forces. This would rather suggest an elevation of the region in recent times. In striking contrast to the features of these rejuvenated valleys are those of the Blantian Valley, where gravel banks and low terraces are frequently to be seen in the lower course.

The alluvial plains of the west coast have given rise to conflicting theories. According to one they are parts of a coastal platform recently raised above sea-level. The opposing view is that a slow sinking of the land has caused a lowering of the transporting power of the rivers, with consequent deposition of their load and filling up of the valleys with alluvium. This is supported by the facts that the main function of the present streams in the plains is deposition, not denudation, and that the coast has been drowned as is well seen at Gaya Bay. It seems probable that both processes have taken place in North Borneo.

It is certain that further and more detailed study will bring to light many interesting problems.

Quaternary deposits

Some problems connected with Quaternary geology have been discussed above, especially those relating to the erosive processes, but oil geologists exploring the country have paid only slight attention to Quaternary accumulations. During this period fluviatile terraces, lacustrine beds, alluvial plains, dunes, beaches and coral reefs were formed. Fluviatile terraces have been observed in several parts, notably around Weston and between the Mengalong and Lakutan rivers in the south-western part of North Borneo. Fluviatile terrace material, or in some cases lacustrine beds, form the large plains of Tenom, Keningau, Suk, Tambunan and Ranau, SE. of the Crocker Range. These plains are really wide, open valleys filled with masses of loose, water-worn boulders, sands and clays, which may often rise in a succession of terraces above the river bed. In the valley of the Padas River above Tenom the terrace sediments are more regularly stratified and have more the character of lacustrine beds.

Coastal swamps underlain by alluvium or sandy alluvial plains form an almost continuous band around the coast of North Borneo.

Dunes, raised beaches or sandy marine platforms appear to be confined to Balambangan Island, Bengkoka Peninsula, to the north and east coasts of the Dent Peninsula and to the north-east coast of Simporna Peninsula.

Recent coral reefs are common, especially off the north and east coast. At the tip of the Dent Peninsula and around Balambangan Island coral reefs are growing on the top of the Plio-Pleistocene series.

CHAPTER IV

Outline of the Geology of North Borneo

Crystalline schists and associated intrusive rocks

WITHOUT a doubt the crystalline schists and the quartz-dioritic to dioritic intrusive rocks associated with them may be regarded as the oldest rocks of North Borneo and evidence of an ancient basement now eroded. The rocks are principally hornblende-schists, chlorite-epidote schists, amphibolites and plagioclase-epidote-hornblende-gneisses. A characteristic feature is the almost complete absence of biotite and the scanty occurrence of muscovite.

Our knowledge of the distribution of the crystalline schists is very incomplete, as the oil geologists, to whom we owe almost exclusively our geological

knowledge of the country, broke off their explorations whenever they came across crystalline rocks.

The main area of distribution of the crystalline schists appears to lie in the south-east part of the country in the area bordering Darvel Bay in the north and west. The middle course of the Segama has cut into these rocks along a 7-kilometre stretch, and the same is true of the Telewas from the elbow where it swings round into an E.–W. direction up to the head-waters. Isolated occurrences of limited extent at Lahad Datu, along the north coast of P. Sakar, in various rivers flowing into Darvel Bay, and in the lower course of the Segama are evidence of a wide distribution of crystalline schists in this area. The old mountains, however, have been completely worn down and for the most part lie buried under Tertiary and Recent sediments. This is borne out by the frequent occurrence of pebbles of crystalline basement rock in the Tertiary conglomerates and in the terrace gravels of the Darvel Bay area.

The southern-most occurrence of crystalline schists on the east coast of the country is represented by a saussurite-amphibolite forming the summit of Gg. Tambuku, a peak in the head-waters of the S.Blantian which can be seen from a great distance. The vertically dipping amphibolite appears to have been thrust unconformably over radiolarites, sandstones and serpentines of the Danau Formation. The extent of the occurrence is very limited; but, on the other hand, crystalline schists found as pebbles in the head-waters of the S.Blantian and the Masmas point to a wider distribution of these rocks. It seems very probable that crystalline schists have played an important part in the formation of that wide area, where no geologist has yet set foot, between the upper course of the Segama and the head-waters of the Tingkayu, Klumpang, Marutai, Masmas and Blantian.

A collection of highly metamorphic rocks of a peculiar kind is to be found in the form of blocks andesitic breccias, agglomerates and conglomerates, in the head-waters of the Tungku and the Pungulupi on the south coast of Dent Peninsula. These rocks are mainly eclogites, amphibolites and hornblende gneisses, which perhaps do not belong to the old crystalline basement but possibly represent derivatives of Danau ophiolites (see Chapter VII, pp. 102-103) which, after suffering deep-seated contact-metamorphism, were brought to the surface with the andesite magma.

North of the Segama, crystalline schists seem to occur only in isolated outcrops of limited extent. Thus gneisses and hornfelses are reported from some of the tributaries of the Kinabatangan-Milian, while amphibolites are exposed on the E. coast of the Kudat Peninsula and on the islands of Banggi and Manawali off the N. coast of the country.

The delimitation of the old crystalline schists from the ophiolites of the Danau Formation presented many difficulties and needs revising. The geologists did not usually distinguish these two formations in their reports and maps. The distinction had therefore to be based mainly on the available rock samples; for many areas, however, such samples were lacking.

We are completely in the dark as to the age of the crystalline schists. Any pronouncement must be considered a matter of feeling; the gneisses and crystalline schists, together with the associated intrusives, may have originated between the pre-Cambrian and the Upper Palaeozoic, and thus represent old crystalline basement rocks.

Slate Formation

During a continental period, which was probably of very long duration, the crystalline basement was eroded and peneplained. It was probably not until much later that a formation of clay and sands was deposited. This formation was subjected to very intense folding and, as a result, shows more or less strongly pronounced dynamic metamorphism. Clay-slates predominate, but as a result of intense cleavage they are often foliated into roofing slates. As a rule the slates are threaded by a fine network of quartz veins or, less commonly, of calcite. Sericite- and chlorite-phyllites occur less frequently, with intercalations of quartzites, foliated arkoses and graywackes.

The slates occur as a N.–S. orientated strip extending from Kinabalu southwards to the head-waters of the Sembakong and thence into Dutch territory. However, the strip is interrupted for a long stretch of some 100 km. where the slates, if they are still present, lie buried beneath Tertiary sediments.

Shales and quartzites similar to those in the Slate Formation also occur among the sediments of the Danau Formation and, to a lesser extent, among the Tertiary deposits. The delimitation of these three formations is therefore very uncertain and needs checking.

The slates cannot be dated exactly because they are unfossiliferous, but a likely age is suggested by

the facts that in the head-waters of the Sembakong the slates are unconformably overlain by basal conglomerates of Eocene age, and that they have undergone one more period of orogenesis than have the Tertiary beds. We can thus fairly safely give the slates a pre-Tertiary age. The problem of the relationship between the age of the slates and that of the Danau Formation remains unsolved. In view of the frequent occurrence of phyllites in the slates and of their absence among the sediments of the Danau Formation, we are inclined to regard the slates as older.

Danau Formation

The typical feature of this formation is the association of radiolarian cherts, sometimes variegated but mostly red, with ophiolites among which serpentine, gabbro, diabase and spilites are of particularly frequent occurrence. In the beds overlying the radiolarian cherts or interbedded with them, variegated calcareous marls bearing micro-foraminifera are occasionally found. These key rocks of the Danau Formation occur in a highly folded and often imbricated sedimentary complex consisting of alternating beds of shales and sandstones. These appear to be of approximately the same age as the radiolarian cherts and the ophiolites, and therefore belong to the sedimentary part of the Danau Formation. In their lithological and structural features these sediments are highly reminiscent of alpine flysch. Sediments and ophiolites are not only imbricated but kneaded together. They form giant breccias, which probably arose through the sub-aqueous penetration of the ophiolites into the as yet unconsolidated sediments, followed by sliding of the whole down the continental slope.

Petrographically the ophiolites are extraordinarily diverse, both as regards texture and mineralogical composition, and besides the widely distributed rock types already referred to, a large number of others occur locally, such as nephrite, jadeitite, peridotites, diorites, basalts, keratophyre and rhyolite. Diabase and spilite tuffs and breccias are also particularly widespread. Some diabases and spilites are characterized by abundant occurrences of pumpellyite. In the light of 15 analyses of various ophiolites from North Borneo, the preponderance of rocks rich in soda over those of the calc-alkali series is clearly manifested.

In the contact zone between the ophiolites and the sediments into which they have intruded, are very widespread contact metasomatic formations of an endomorphic and exomorphic nature. All transitional stages are exemplified from those with the slightest trace of re-crystallization in the case of radiolarian cherts and limestone marls, through varying degrees of silicification and calcification up to the complete replacement of the primary mineral content of the ophiolites by secondary mineral paragenesis, in which the original texture is generally preserved. The clayey-sandy sediments were transformed at the ophiolite contacts to adinole schists and spilosites.

The question of the age of the Danau Formation has not been definitely answered, but there are clues which, on the basis of fossil content, suggest a Mesozoic to Paleocene age. The radiolaria in the radiolarian cherts unfortunately do not permit of any age determination. Nevertheless, in the calcareous marls occurring with the radiolarites, microforaminifera are present, from which a Mesozoic to Paleocene age may be deduced (cf. Appendix III). In various localities Tertiary calcareous sandstones, whose age could be determined with certainty from macroforaminifera as ranging from Eocene to Miocene, lie unconformably upon the Danau Formation. This also suggests that the age of the Danau Formation is predominantly pre-Tertiary. Where fossiliferous calcareous sandstones of Tertiary age are absent, no boundary between the sediments of the Danau Formation and the Tertiary clay-sandstone complex can, however, be established. Sills and stocks of basalt were also observed in Tertiary sediments on the east coast of the Bengkoka Peninsula and in the basin of the Kinabatangan-Milian. Should these prove to be ophiolitic intrusions of basalt, this would mean that such intrusions persisted into the Middle Tertiary.

The absence of any definitely ascertainable boundary between the sediments of the Danau Formation and the Slate Formation has already been mentioned in the preceding section. Locally also, there is uncertainty as to the delimitation between the ophiolites, with their contact products, and the crystalline schists.

From these considerations it follows that our information as to the area covered by the Danau Formation is very incomplete, because their delimitation from both the overlying and underlying beds is uncertain, and especially because broad areas in which the presence of Danau Formation is suspected have not been investigated by geologists. It is certain, though, that the Danau Formation is

very extensive in the south-east of the country. In the Kinabalu area it accompanies the Slate Formation; in the Kudat and Bengkoka peninsulas it occurs in innumerable eroded anticlinal crests in the Tertiary area, and finally it occupies wide areas in the islands to the north, particularly in P. Banggi and P. Manawali.

Tertiary Formation

The greater part of North Borneo is covered by Tertiary sediments. The stratigraphy and tectonics of these rocks were studied in some detail by the oil geologists exploring the country, and the microfaunas of the Tertiary sediments were investigated by the palaeontologists. On the evidence of lithology and of established transgressions and unconformities, the Tertiary series could be subdivided in the northern and eastern parts of the country. The four-fold division of the Tertiary sequence, found by the field geologists, was dated as follows by micro-palaeontological research:

Plio-Pleistocene	in reef and paralic facies
local disconformity or unconformity	
Tertiary e_5–*f* (approx. equiv. Miocene)	in reef, paralic, marine shallow-water and volcanic facies
regional unconformity	
Tertiary e_{1-4} (approx. equiv. Aquitanian)	in reef, marine shallow-water and volcanic facies
local unconformity	
Tertiary a–b (*Eocene*)	in reef and semi-arid marine epi-continental facies
regional unconformity	
Pre-Tertiary inclusive of Paleocene.	

The fundamental palaeontological data are to be found in Appendix II, and the detailed stratigraphy of the Tertiary sediments, which show considerable change in time and in space, is set down in correlation Tables I and II.

In some parts of North Borneo the Tertiary sediments comprise many formational stages and reach a thickness of up to 10,000 m., while in other areas only some upper part of the sequence is deposited. Not only the beds of Tertiary a-b age, but also those of Te_{1-4}, Te_5-f and of Plio-Pleistocene age may be found transgressively overlying the pre-Tertiary formations. This demonstrates considerable vertical movements and the action of erosion during Tertiary times. In North Borneo no geosynclinal basins were formed in this period. The waters of the various basins apparently never reached any considerable depth. Shallow basins subsided and were simultaneously filled with predominantly arenaceous sediments.

In Eocene times (Ta-b) the pre-Tertiary of North Borneo appears to have been locally and temporarily dry land exposed to oxidation weathering and erosion. It was also partly submerged and covered by a transgressive shallow sea in which epi-continental marine sediments, such as red-brown sandstones and shales, containing much salt, and reef limestones were deposited.

In Tertiary e times (Te) the greater part of North Borneo was submerged and the waters had free access right across the country, thus connecting the important Tertiary basins of Sarawak-Brunei, Tarakan-Bulungan and north-eastern Borneo.

The subsidence of the basins was interrupted by diastrophism near the end of the Te stage. Part of the pre-Tertiary and the Tertiary sediments were isoclinally folded and imbricated and subsequently eroded. The maximum movement took place between Te_4 and Te_5. This is the most important Tertiary orogeny of North Borneo, by which the present structural picture was essentially delineated. The isoclinal Tertiary folds bend around the edges of the pre-Tertiary blocks, which acted either as moving masses or as rigid blocks determining the configuration of the folds. It appears that this period of diastrophism was connected with and followed by magmatic intrusions and extrusions. Mt. Kinabalu (4,100 m.), the highest mountain in the Malay Archipelago, is formed of a Tertiary intrusion of quartz-monzonitic to granodioritic composition; in the surroundings are minor occurrences of the same rock. Tertiary volcanic rocks are to be found mainly on the Simporna and Dent peninsulas of the east coast. They are important links in the chain of Tertiary volcanic rocks which extends from the Philippine Islands across the Sulu Archipelago toward Borneo (see Enclosure II). This volcanism was of a highly explosive type and produced, apart from andesitic lavas, mainly volcanic agglomerates, tuff breccias, tuffs and

tuffites. The pyroclastic rocks are interbedded in the Tertiary sediments and locally contain foraminifera, a fact which proved to be very helpful for the determination of the age of the volcanic explosions (late Te). If some sporadic and problematic occurrences of basaltic and gabbroid rocks in the Tertiary sequence be disregarded, the Tertiary igneous rocks all deriving from the same magma are oversaturated in silica and belong to the calc-alkali series, as is especially indicated by the high normative and modal anorthite content of 14 chemically analysed rocks. Some types are rich in potash (Kinabalu).

After the important phase of diastrophism connected with magmatic activity, and the subsequent period of erosion of late Te age, shallow-water conditions prevailed again. The transgressive Te_s-f formation consists at the base of reef-limestones and, in the middle and upper parts, of a very well-bedded alternation of sandstones, clays and shales with much carbonaceous matter. These marine shallow-water sediments cover a large portion of north-eastern, central and southern North Borneo. They prove that in Miocene times vast areas of the country were still submerged. The Tertiary e_s-f is preserved in some flat synclinal basins, whose peculiar, almost circular shape, is seen in Figs. 6 and 7. It seems impossible to explain such structures by tangential compression only, without taking into consideration local downward movements.

Tertiary formations younger than Tf, i.e. younger than Miocene, have been found only on the Dent Peninsula, on Balambangan and Mangalum islands and on the Klias Peninsula. They are developed either in paralic or in reef facies and are gently folded. There are indications in the Dent Peninsula that sedimentation and gentle folding proceeded in a rhythmic alternation, or at times simultaneously, from the Miocene up to the Quaternary.

On the mainland of North Borneo a varied Tertiary sequence many thousands of metres thick is found. However, it is remarkable that on the northern adjacent islands of Banggi and Balambangan all stages of the Tertiary are developed exclusively in reef facies with reduced thickness. It appears that shelf conditions existed on these islands throughout Tertiary times. During the whole period the pre-Tertiary basement was either at shallow depth or slightly above water.

The Tertiary folds are cut off, almost at right-angles to the direction of strike, by the NE. coast of North Borneo, which is fronted by the Sulu Sea (3–5,000 m. deep). This fact suggests that the Sulu Sea is comparatively recent. This deep sea basin is bordered toward the Celebes Sea by the Tertiary volcanic arc mentioned above (in the Philippine Islands partly of Quaternary age), and towards the China Sea by a belt of pre-Tertiary rocks of the Danau Formation (Palawan Island), which forms the direct prolongation of the zone of Danau uplifts crossing North Borneo from Darvel Bay via the Segama and Labuk areas towards Banggi Island.

A geological feature of Recent age in North Borneo, which appears to be related to the formation of the Sulu basin, is the range of mud-volcanoes found in the north-eastern part of the country. They are aligned in a narrow, curved zone, 150 km. long, which runs obliquely to the Tertiary structures, but which is concentric with the contour lines of the Sulu Sea. Inflammable gas, salt water and mud are produced by these volcanoes, and large boulders of Tertiary and pre-Tertiary sediments and pre-Tertiary ophiolites and crystalline schists are ejected. No trace of oil has been found. These mud-volcanoes are certainly of deep-seated origin and appear to be due to diapyric perforations of the basement, but their mechanism has not been explained. However, their independence of the Tertiary structures and their arrangement along the south-western coast of the Sulu basin, which is situated on the concave side of the mud-volcano arc, are conspicuous. In the Moluccas, analogous mud-volcanoes of problematic origin are arranged around the Banda Sea.

Of different origin are the mud-volcanoes found on the Klias Peninsula and adjacent islands. They occur in oil-bearing formations of Te age, follow Tertiary anticlinal crests and seem to be connected with the release of gas pressure from the underlying beds.

Apart from those in the Klias Peninsula, oil-seepages occur on Mangalum Island, at Sequati in the Kudat Peninsula and on Sebatik Island. They are derived from formations of Te and of Plio-Pleistocene age. In the eastern part of North Borneo only gas-seepages have been found.

North Borneo emerged from the sea in comparatively recent times. During the Pliocene and Quaternary it gradually became dry land, and in the course of epeirogenetic movements and of erosional and accumulative processes the present relief was shaped. The uplift was neither equal nor continuous throughout the country, as is shown by differing coastal types and by sub-recent

changes of river courses. Characteristic features of the present physiography are the eccentric position of the dominant mountains, the independence of prominent orography of the main watersheds, and the occurrence of some finely dissected peneplains in the interior.

Occurrences of useful minerals

The ophiolites have locally been ore-bearers. In contact with the radiolarites, manganese ores frequently occur in small quantities, accompanied in one case by the rare mineral inesite. Chromite has occasionally been found in the serpentines. The secular weathering of the peridotites has given rise locally to the formation of pisolitic limonites and laterites rich in iron. Various insignificant occurrences of pyrites, chalcopyrite, sphalerite, pyrrhotite and arsenopyrite are connected with the ophiolites. Several of these finds have given rise to temporary exploitation.

Gold was formerly washed in the middle course of the Segama and in the Diwata and Subahan rivers, which flow into the western part of Darvel Bay. It is uncertain whether the primary deposits are connected with the ophiolites or with the crystalline schists.

Lignite seams occur in various parts of the Tertiary deposits and have been successfully exploited. The discovery of oil-seeps in the Klias Peninsula, on P. Mangalum, 60 km. to the north of the Klias Peninsula, and along the Sequati on the west coast of the Kudat Peninsula, led to drilling operations with, however, unsuccessful results. Equally unproductive of oil was a well sunk at the north-western end of the island of Sebatik in the vicinity of the Dutch frontier (SE. coast of B.N.B.).

Thus the mineral deposits already known are but meagre, and until new and better occurrences come to light, the riches of the country must be considered to be those visible at the surface in the form of fertile soil and extensive forests with their precious timber.

CHAPTER V

Tertiary Sediments and Tectonics

1. Formational Correlations and Micro-Palaeontology

TERTIARY sediments cover roughly three-quarters of the territory of North Borneo. Most of the Tertiary forms a continuous cover in the coastal regions as well as in the interior and surrounds the pre-Tertiary uplifts.

Although the various parts of North Borneo have been surveyed by different geologists, their subdivisions could be satisfactorily correlated all over the country. Owing to considerable changes in facies, lithological correlations were in some cases difficult to establish. There are, however, beds with marked lithological characteristics which show a widespread distribution, such as: the red and green shales and chocolate-brown sandstones of the Kulapis Formation (Ta-b); the very coarse conglomerates built up of predominantly volcanic material in a tuffaceous matrix (Tungku Formation, Te); the very well bedded alternating shale-sandstone series with plant remains (Bongaya Formation, Te_s-f); and the sands, sandstones, marls and reef-limestones of the Pliocene Togopi Formation. The main criteria for the subdivisions and correlations have been: (I) lithology of the sediments, (II) palaeontological evidence, (III) established transgressions and unconformities. Apart from these reliable indications, in some cases the different degree of folding and divergencies in the direction of strike between different formations have also been used. As far as possible the stratigraphical results have been compiled in concise schedules, and the reader is referred to Tables I and II. The following remarks are explanatory.

In some places only the upper part of the Tertiary series has been deposited and is lying transgressively upon the pre-Tertiary. It was possible in the northern and eastern parts of the country to distinguish in the field *three major unconformities* within the Tertiary series. These stratigraphical

TABLE I

STRATIGRAPHICAL CORRELATION TABLE

Summary of Tertiary Formations Exposed in Northern and Eastern British North Borneo

Approximate European equivalent	Letter classification	Approximate equivalents based on smaller foraminifera: Miri	Sarawak	Tarakan	Banggi-Balambangan Islands (W. Schneeberger): Formation	Character	Labuk Bay (W. Schneeberger): Formation	Character	Lower Kinabatangan Area (E. Wenk): Character	Middle Segama Area-Darvel Bay (J. Wanner, K. Stamm, P. Leicester): Formation	Character	Dent Peninsula (E. Wenk e.a.): Formation	Character
PLIO-PLEISTOCENE		Liang			Timohing	reef-facies: *coral limestones* and *marls* transgressive upon pre-Tertiary on Balambangan Island.						Togopi > 200 m.	reef-facies: loosely cemented and brecciated *reef-limestones, sandstones and sands:* light-grey *sandy marly clays* with rich and typical fauna of foraminifera, gastropoda, lamellibranchiata and corals.
					(unconf.)							? disconformity	
												Ganduman 1,000 m.	paralic facies: *mainly clays*, often *carbonaceous* and with many *lignite* seams; intercalated layers of silty to sandy and marly clay; hard calcareous siliceous concretions; fossil resin and pyrite common; foraminifera of Togopi type scattered throughout, but poor in number and in species; gas indications.
												? disconformity	
MIOCENE		Seria?		Sadjau?								Maruap 200–500 m.	soft, medium- to coarse-grained limonitic *sands* and *sandstones* with transitions into *conglomerates:* foraminiferal sandy-marly *clays* with limestone lenses; carbonaceous clays.
												? disconformity	
	e_5–f	Miri		Upper Birang-Simengaris-Santul		*limestones* and calcareous *sandstones* with *Trybliolepidina rutteni*, T. *martini*, *Nephrolepidina ferreroi*, *N. callosa*, *Miogypsina* spp.							marine shallow-water to paralic facies: *tuffitic* and sandy, rarely marly, *clays* with foraminifera, gastropoda and scattered plant-remains; gas indications. alternations of grey *sandstones* and *clays* or shales; few conglomeratic sandstones; in lower part of formation *Miogypsina cushmani*, *Alveolinella bontangensis*, *Trybliolepidina martini* 3 m. *basal conglomerate* with coral and shell fragments in S.Tungku.
							Bongaya ~ 5,000 m.	paralic facies: alternations of soft, white or limonitic *sandstones*; foraminiferous *sandy clays* with plant-remains and cyrenidae; greenish-blue *clays*, *carbonaceous* clays and thin *coal* seams; cliff-forming, gritty, limonitic sandstones and white tuffitic sandstones at the base.	paralic to reef-facies: well-bedded and alternating series of grey *shales* and *sandstones* with many plant-remains and limonitic concretions; coral-limestones and *limestone-breccias* with *Miogypsina* spp., *Nephrolepidina angulosa*, *N. isolepidinoïdes*, *N. parva* at the base of formation at Supu and Gomantong; thin *basal conglomerate* in S.Mananggol.	Tapadong ~ 100 m.	reef-facies: *coral-limestone* with *Nephrolepidina ferreroi*, *Alveolinella bontangensis*, transgressive upon the pre-Tertiary at Batu Tapadong (Segama).	Sebahat 800–1,000 m.	
							unconformity					*unconformity*	
AQUITANIAN (Oligocene)	e_{1-4}	Pre-Miri		Middle-Birang	BANGGI – BALAMBANGAN: reef-facies	*Miogypsinoïdes dehaarti*, *Nephrolepidina* spp., *Eulepidina* spp., *Spiroclypeus* spp.	Sugut several thousands of metres	marine littoral facies: hard, unbedded and well-jointed, dark grey, massive, fine gritty *sandstones* with big globular concretions and honeycomb structure; assemblage of laminated coaly sandstones; light blue, hard sandstones, brown limonitic *sandstones* alternating with blue *clays* and sandy clays; *tuff breccias*; thick massive, locally conglomeratic, sandstones at the base near Sandakan-Berhala.	marine littoral to reef-facies: badly-bedded, massive, quartzitic mica-*sandstones* with brown weathering crust; reef-*limestones* with abundant *Eulepidina* spp., *Heterostegina borneënsis*, *Spiroclypeus* spp.; in lower part alternations of grey *shales*, *marly clays* with small foraminifera, sandy clays and grey quartzitic *sandstones* with quartzitic and limonitic concretions; unconformity not proven in Kinabatangan area.	Tabanak > 1,200 m.	marine shallow-water-volcanic facies: 800 m. very coarse, non-calcareous *conglomerate* with predominantly volcanic components; *andesite dykes* and *tuffs*; thin intercalations of shale and sandstone, large fragments of silicified wood and coal; grey *clays* and foraminiferal *marls* alternating with light-grey *sandstones* and *shales*; sandy limestones; basal conglomerate; series transgressive upon pre-Tertiary at Lahad Datu.	Tungku > 1,000 m.	pred. volcanic in Tungku area marine shallow-water facies in NE. Dent Peninsula: *conglomeratic accumulation* of up to 1 cu. m. big volcanic and metamorphic boulders in tuffitic cement; *block-lava* alternating with *tuff* beds; *volcanic dykes* and domes; brownish and greenish, colour-banded, hard *shales*; conglomeratic sandstones with silicified wood; grey clays and sandy clays; volcanic material decreasing toward E. and N.; series transgressive upon pre-Tertiary in S.Tungku.
							unconformity					*unconformity*	
EOCENE	(a)—b					*Camerina*, *Discocyclina*, *Pellatispira*.	Kulapis several thousands of metres	semi-arid epi-continental facies: mainly chocolate-brown to violet, fine-grained gritty, massive *sandstones* and dark-grey, quartzitic, well-jointed sandstones with pillow-structure; intercalated with hard, red-brown non-calcareous clays and shales, no fossils; *salt-seeps* and *mud-volcanoes*; gabbro intrusions and tuffs. formation transgressive on pre-Tertiary.	semi-arid epi-continental facies: grey, chocolate and red-brown, gritty *sandstones* with interbedded layers of hard, red-brown or green, rarely marly and never sandy *shales* and clays; formation barren of fossils; many *salt-seeps* and *mud-volcanoes*.	Darvel Bay	marine epi-continental facies: mainly grey to red-brown, well-jointed *sandstones* with large globular concretions; intercalated layers of grey, green and red shales and marls with *Discocyclina* and *Camerina baguelensis*; tuffitic breccias; reddish sandy limestones; *salt-seeps*. thick, calcareous, *basal conglomerate* overlying the pre-Tertiary in Upper Segama River.		
							unconformity					*unconformity*	

PRE-TERTIARY DANAU FORMATION (incl. Paleocene ?)

TABLE II

STRATIGRAPHICAL CORRELATION TABLE

Summary of Tertiary and Pre-Tertiary (Slate) Formations Exposed in the Western, Southern, and South-Eastern Parts of North Borneo

Approximate European equivalent	letter classification	Klias (G. Niethammer, W. Hotz)		W. Coast and Crocker Range (G. Niethammer, W. Hotz)	Interior (P. J. Roothaan and E. Wenk)		Sarudong-Kalabakang Area (M. Reinhard e.a.)	
		Formation	Character	Character	Formation	Character	Formation	Character
PLIO-PLEISTOCENE		Kalugus	unconsolidated white *sands*; soft yellowish *sandstones* and sands; greyish *shales*.					
		unconformity						
MIOCENE	e_5-f	Mensian Batu Punggul Age uncertain (Miocene or Pliocene)	fluviatile to paralic facies: 1,000 m. light-grey *shales* and yellowish soft *sandstones* with plant-remains and *coal seams*; locally overlying Sabong Formation; oil indications. local disconformities 0–700 m. very hard, fluviatile *conglomerates* with intercalated beds of shale and sandstone with plant-remains; sandstone increasing toward S.		Bongaya 6,000 m.	reef facies to paralic facies: very well bedded alternation of grey *clay*, *shale* and *sandstone* with *coaly films*, often well-preserved plant-remains, few seams of glance coal, small limonitic, quartzitic and calcareous concretions; intercalated *coral-limestones* with *Miogypsina*, *Nephrolepidina* in S.Pinanga and Bayudon-Kuamut. calcareous sandstone with lamellibranchiata, *Miogypsina*, *Miogypsinoides*, *Nephrolepidina* in S.Kuamut above 2 m. *basal conglomerate*, showing white quartzitic pebbles in an argillaceous-sandy matrix.	Bongaya several thousands of metres	reef-facies to paralic facies: in Sarudong region: hard, thickly bedded *sandstones* (Susui) with thin intercalations of shale and *coal*; overlying a series of dark-grey *shales* (Tambalunan) with calcareous concretions and containing *Alveolinella bontangensis*; in Kalabakang region: very well bedded alternations of *shale* and *sandstone*; few coral-*limestones* with *Miogypsina* and *Nephrolepidina*.
		unconformity			unconformity		? unconformity	? — ? — ?
AQUITANIAN (OLIGOCENE)	e_{1-4}	Sabong > 500 m.	marine shallow-water to reef facies: upper part formed by *clays*, *marls*, *sandstones* and *limestones* containing corals, mollusca and abundant *Nephrolepidina*, seldom *Miogypsina*. hard, greenish-grey, badly bedded *shales* with intercalated beds and lenses of very hard, fine-grained quartz-sandstone; limonitic concretions and plant-remains; sandy limestone with *Eulepidina*, *Heterostegina*; oil-seeps and mud-volcanoes.	marine littoral facies: uniform, undivided, thick series consisting predominantly of greyish and yellow-grey, soft and hard *sandstone* or siltstone, locally carbonaceous, thin and thick layers of grey and characteristic red and green *shales*, remarkably low in sand content and barren; carbonaceous sandy shales and tiny coal seams are rare; in coastal area Papar-P. Gaya-Usukan and along Crocker Range mainly sandstones; shales common in intermediate area; red shales decreasing toward N. where formation becomes fossiliferous; at Tg. Taburan Tamid (SW. Kudat Peninsula) coarse-grained *sandstone* with *Camerina*, *Discocyclina*, *Asterocyclina*, associated with red sandstone and red shale.	Tongod several thousands of metres	reef-facies: *coral-limestones* with *Nephrolepidina* and *Eulepidina* at top of formation (Sarupi-Kuamut); mainly greenish to bluish-grey, hard, badly bedded, heavily jointed, fine to medium-grained mica-*sandstones* with conspicuous kaolinized feldspar grains, characteristic convex erosional forms, yellow-brown weathering crust and big globular concretions; no fossils; few and thin intercalations of clay; marine littoral facies: *in Milian and Talangkai region:* above-mentioned sandstones are in the middle part of the formation intercalated with layers of red, grey and green *shale*; gradual transitions into the following variegated series: *in Sapulut - Kuamut region:* Batu Punggul *coral-limestone* with *Eulepidina* in above sandstone; 50 m. very quartzitic *basal conglomerate*, in S.Sapulut on Slate Form., in S.Kuamut on Danau Form. semi- arid epi-continental facies: characteristic chocolate, red-brown and crimson-red *sandstones* with intercalated layers of grey, red and green, non-calcareous and non-sandy shales; no fossils found; many *salt-seeps*; in Milian area this coloured series overlies the Danau Formation unconformably and in Talangkai area the Slate Formation.	Kapilit several thousands of metres	shallow-water to paralic facies: alternating series of neutral coloured, hard, well-banked *sandstones* with red-brown weathering crust and many limonitic and calcareous concretions, *conglomeratic sandstones*, grey, sandy, seldom *marly clays* and *shales*; coal seams (Silimpopon); grey, hard, badly bedded quartzitic mica-sandstone; thick, hard, basal conglomerate with fist-sized, well-rolled quartzitic pebbles in sandy matrix in S. Tiagau.
EOCENE	(a)-b		reef-facies: *limestones* containing *Camerina* and *Discocyclina* at the base of the formation in S.Pangas, S.Kingaran (both tributaries of S.Pegalan), S.Sungei, S.Mangaris and S.Bengkongan (S. Kudat Peninsula), overlying the pre-Tertiary.					
		unconformity			unconformity		unconformity	
PRE-TERTIARY				dark, *lustrous clay-slates*, often developed as *roofing slates*, intercalated thin and thick layers of hard, *quartz-sandstone* or *greywacke*; characteristic thin *quartz veins* spread throughout the formation; no fossils; formation found in the Trusmadi Mountains, at Tenom and W., S. and E. of Kinabalu.	Slate several thousands of metres	rhythmically alternating series of decimeter-thick layers of *quartz-sandstone* and *greywacke* showing transitions into *quartzites* and of centimetre-thick layers of dark *clay* and *shale* changing into blackish *clay-slates*, *silky slates* and *phyllites*; thick masses of slates; thin *veinlets of quartz* and rarely calcite are characteristic; no fossils and no igneous intrusions; formation found in Sapulut-Talangkai-Tagul area.	Kalabakang several thousands of metres Age uncertain (Eocene or pre-Tertiary)	in lower and middle course of Kalabakang River: grey, concretionary, crumbling, sandy *shale formation* with *sandstone* inter calations showing ripple-marks locally; bedding poor and obscured by cleavage-, fault- and joint-planes; no fossils; in middle and upper course of Tiagau River: sandstones seldom calcareous, whole series becoming gradually *metamorphic*: dark-grey *clay-slates* and *phyllites* alternating with dark *quartzitic sandstones*; series *veined* with *quartz* and calcite; locally quartz crystals in joint-fissures; no fossils and no igneous intrusions.

breaks of regional importance were consequently used as key horizons and afforded a *four-fold division of the Tertiary of North Borneo.*

Formations	*Letter Classification*	*European Nomenclature*
Togopi-Ganduman	—	approx. equiv. Pliocene
disconformity or unconformity		
Bongaya-Dent Peninsula	Tertiary e_5–f	approx. equiv. Miocene
unconformity		
Sugut-Tungku	Tertiary e_1–$_4$	approx. equiv. Aquitanian (Oligocene)
unconformity		
Kulapis-Darvel Bay	Tertiary a–b	equiv. Eocene
unconformity		
	Pre-Tertiary (+ Paleocene)	

The results of *micro-palaeontological* examination of a fairly large number of rock samples proved most helpful for stratigraphical correlation. The micro-palaeontological research was confined to the study of the larger and the smaller foraminifera. Since the species which characterize the fauna of the East Indian Tertiary are quite different from those of the European region, the European subdivisions of the Tertiary cannot be applied to the Indonesian series. For this reason I. M. van der Vlerk and J. H. F. Umbgrove (1927) have introduced a *letter classification* of the East Indian Tertiary, based on the ranges of the larger foraminifera. It has been assumed that these ranges, established in the Netherlands East Indies, generally agree with those of North Borneo, and therefore the letter division has also been applied to the Tertiary of the Colony of North Borneo. In accordance therewith the four-fold division of the Tertiary sequence in the eastern and northern parts of the country could be dated as above.

The series younger than Tertiary f did not furnish larger foraminifera of diagnostic value and could not therefore be classified in the letter-system.

For the sake of convenience the approximate European stratigraphic equivalents have also been indicated above; the top of the Tf approximately coincides with the base of the Pliocene and the Te_{1-4} corresponds approximately with the Aquitanian, which, according to recent investigations (vertebrata), is now thought to be of Oligocene age.

In North Borneo no diagnostic foraminifera of Tc and d age have been encountered and, since no series of any importance have been reported from the interval between those determined as Tb and those recognized as Te, the conclusion seems justified that the Tc-d is either very thin or was not deposited.

The stratigraphic position of the lower two of the above-mentioned unconformities in the Tertiary of eastern and northern North Borneo could thus, on the basis of larger foraminifera, be indicated as being: one at the base of Te, i.e. at the base of the Aquitanian (uppermost Oligocene), and the other at the base of Te_5, i.e. at the base of the Miocene.

The study of the larger foraminifera has also contributed to our geological knowledge of the Tertiary of the northernmost parts of North Borneo in proving the occurrence of *reworked* Eocene foraminifera which were encountered in beds of Te-f age. The contamination of Te-f by Eocene foraminifera proves the erosion of parts of the Eocene during Te-f time within certain areas.

The following *larger foraminifera* could be identified. The species or genera marked * are of diagnostic value; such forms are entirely restricted to, or mainly occur in, one of the three stages mentioned.

1. *Tertiary a–b* (equiv. Eocene).
   - **Camerina* sp. (allochthonous in Te_1–e_4).
   - „ **thalicus* L. M. Davies.
   - „ **baguelensis* Verbeek.
   - **Discocyclina* sp.
   - „ **umbilicata* Defr.
   - **Pellatispira* sp. } allochthonous in Te_1–e_4 and Te_5–f
   - „ **mandaraszi* Hantken
   - „ *var. *provalei* Yabe
2. *Tertiary* e_1–e_4 (approx. equiv. Aquitanian, Oligocene)
   - *Lepidocyclina* sp.
   - „ *flexuosa* Rutt.
   - „ *acuta* Rutt.
   - „ *insulae-natalis* Jones and Chapman.
   - „ *munieri* Lem. and Douv.
   - „ (*Eulepidina*) sp.
   - „ („) **dilatata* Michelotti.
   - „ („) *formosa* Schlumb.
   - „ („) **planata* Opp.
   - „ („) **atuberculata* v.d.V.
   - „ (*Nephrolepidina*) sp.
   - „ („) *sumatrensis* Brady.
   - „ („) „ „
   - „ („) var. minor Ruff.
   - „ („) *angulosa* Prov.
   - „ („) *isolepidinoides* v.d.V.
   - „ („) *borneensis* Prov.
   - „ („) *inflata* Prov.

Lepidocyclina (*Nephrolepidina*)**verbeeki* Newt. and Holl.
„ („) *mariae* R. Douv.
„ („) *smithi* H. Douv.
„ (*Trybliolepidina*) *transiens* Umbgr.
Miogypsina sp.
„ (*Miogypsinoides*) *dehaarti* v.d.V.
„ („) *complanata* Schlumb., var. *bantamensis* Tan.
Heterostegina sp.
„ *borneensis* v.d.V.
„ **depressa* d'Orb.
Spiroclypeus sp.
„ **leupoldi* v.d.V.
„ **pleurocentralis* Carter.
„ **margaritatus* Schlumb.
„ „ „ *var. *umbonata* Yabe and Hanz.
„ **tidoenganensis* v.d.V.
Cycloclypeus sp.
„ *communis* Martin.
Gypsina sp.
„ *globulus* Reuss.
Neoalveolina pygmaea Verbeek.
Linderina Paronai Osimo.
Trillina howchini Schlumb.
Carpenteria sp.
Amphistegina sp.
„ *lessonii* d'Orb.
Operculina sp.
Operculinella sp.
„ *venosa* F. and M.

3. *Tertiary* e_5*–f* (approx. equiv. Miocene).
Lepidocyclina sp.
„ *flexuosa* R.
„ (*Eulepidina*) sp.
„ („) *andrewsiana* Jones and Chapman
„ („) *formosa* Schlumb.
„ (*Nephrolepidina*) sp.
„ („) *sumatrensis* Brady.
„ („) **ferreroi* Prov.
„ („) *angulosa* Prov.
„ („) *callosa* Scheffen.
„ („) *verrucosa* Scheffen.
„ („) *isolepidinoides* v.d.V.
„ („) *borneensis* Prov.
„ („) *parva* Opp.
„ („) **douvillei* Yabe.
„ („) *inflata* Prov.
„ *(*Trybliolepidina*) sp.
„ („) **rutteni* v.d.V.
„ („) **martini* Schlumb.
Miogypsina sp.
„ **cushmani* Vaughan, var. *Indonesiensis* Tan.
Miogypsina **kotôi* Hanz, var. *bispiralis* Tan.
„ (*Miogypsinoides*) *dehaarti* v.d.V.
Heterostegina sp.
„ *borneensis* v.d.V.
Spiroclypeus sp.
Cycloclypeus sp.
„ *communis* Martin.
„ **eidae* Tan.
Gypsina sp.
„ *globulus* Reuss.
„ *plana* Carter.
Neoalveolina pygmaea Verbeek.
Borelis melo F. and M.
**Alveolinella bontangensis* Rutten.
„ *globulosa* Rutten.
Linderina paronai Osimo.
Trillina howchini Schlumb.
Amphisorus hemprichii Ehrenb.
Archaias angulatus F. and M.
Carpenteria sp.
Amphistegina lessonii d'Orb.
Operculina sp.
Operculinella venosa F. and M.

For the occurrence of the larger foraminifera in the various formations, see correlation Tables I. and II. The faunal assemblages of the 123 foraminiferal limestone samples determined by I. M. van der Vlerk are listed in Appendix II.

The post-Eocene Tertiary beds from Labuk Bay, the Lower Kinabatangan area and the Dent Peninsula were examined for *smaller foraminifera*. These have been compared with the fauna from the Miri-Brunei region on the one hand and from the Tarakan basin on the other. The correlations based on the study of the smaller foraminifera can be outlined as in the table below.

A list of the smaller foraminifera encountered in the post-Eocene formations of North Borneo is given below.

Series younger than Tertiary f (approx. equiv. Pliocene): Togopi and Ganduman formations (Dent Peninsula).

Amphistegina spp. *Calcarina* sp. *Cibicides* sp. *Elphidium* spp. *Loxostoma* sp. *Nonion* sp. *Operculina* sp. *Operculinella* sp. *Peneroplis* sp. *Quinqueloculina* spp. *Rotalia* spp. *Textularia* sp. *Triloculina* sp.

Tertiary e_5*-f* (approx. equiv. Miocene): Sebahat

Miri-Brunei		*Labuk Bay-Lower Kinabatangan area*		*Dent Peninsula*		*Tarakan*
Liang Formation	=			Togopi Formation		
				Maruap Formation	=	Santul and marine Telassau Formation
Miri Formation	=	Bongaya Formation	=	Sebahat Formation	=	Simengaris and Upper Birang Formation
Pre-Miri Formation	=	Sugut Formation	=			Middle Birang Formation

Formation (Dent Peninsula) and Bongaya Formation (Labuk and Lower Kinabatangan area).

Ammobaculites sp. *Ammodiscus* sp. *Amphistegina* spp. *Asterigerina* sp. *Bathysiphon* sp. *Bolivina* spp. *Bolivinita* sp. *Bulimina* spp. *Cibicides* spp. *Cristellaria* spp. *Cyclammina* sp. *Dorothia* sp. *Elphidium* spp. *Epistomina* sp. *Eponides* sp. *Globobulimina* sp. *Glomospira* sp. *Gyroidina* spp. *Haplophragmoides* sp. *Karreriella* sp. *Lamarckina* sp. *Loxostoma* sp. *Nodosaria* spp. *Nonion* spp. *Operculina* sp. *Operculinella* sp. *Peneroplis* sp. *Planularia* sp. *Plectofrondicularia* sp. *Pullenia* sp. *Quinqueloculina* spp. *Rotalia* spp. *Sigmoilina* sp. *Siphogenerina* sp. *Siphonodosaria* sp. *Sphaeroidina* sp. *Textularia* spp. *Uvigerina* spp. *Virgulina* sp.

Tertiary e_1-e_4 (approx. equiv. Aquitanian, Oligocene): Sugut Formation (Labuk and Lower Kinabatangan area).

Ammodiscus spp. *Bathysiphon* spp. *Bulimina* spp. *Cibicides* spp. *Cyclammina* spp. *Dorothia* sp. *Eponides* sp. *Glomospira* sp. *Gyroidina* sp. *Haplophragmoides* spp. *Kakkeriella* sp. *Nodosaria* spp. *Nonion* sp. *Pullenia* sp. *Rotalia* sp. *Sigmoilina* sp. *Siphonodosaria* sp. *Sphaeroidina* sp. *Textularia* sp. *Trochammina* sp. *Uvigerina* sp. *Vulvulina* sp.

2. Sedimentary Record and Palaeogeography

a. *Tertiary a-b* (Eocene)

All proven Eocene (Ta-b) sediments of North Borneo are *epi-continental* deposits. The *transgressive* character of the Eocene beds upon the peneplained pre-Tertiary *incl. Paleocene* is clearly evidenced by basal conglomerates, reported by Wanner (1921) from the Segama River, and by sandstones and limestone breccias with fragments of pre-Tertiary igneous rocks and cherts found on Banggi Island and Kudat Peninsula. It is difficult to say with certainty whether British Borneo was entirely or only partly submerged during Eocene times. Beds of Te age directly overlap the pre-Tertiary in many parts of the country. Thus, in these areas the Eocene might have been eroded off or might never have been deposited. A strong argument in favour of the existence of islands in a shallow Eocene sea and of lagoons surrounded by pre-Tertiary uplifts, is seen in the development of the facies. The Eocene beds are predominantly arenaceous, variegated and mostly unfossiliferous. In this chocolate, red-brown and even crimson-red sandstone series with intercalated grey, red and green shales, many brine springs occur. The formation has much in common with the Germanic, east-alpine and arctic Permo-Triassic. The coloured Eocene is considered as having been built up from pre-Tertiary material that had lain exposed to lateritic weathering during a post-orogenic period of prolonged erosion, and was then deposited in nearby shallow basins and lagoons which may temporarily have run dry. The salinity of the water had been so high that the development of organisms such as would normally cause reduction of the ferric iron was inhibited.

The microscopic study of a dark, red-brown, fine-grained sandstone from the west coast of the Kudat Peninsula (Nh. 128), occurring in the vicinity of a palaeontologically proven Eocene calcareous sandstone with Danau-fragments (Nh. 130, Tg. Taburan Tamid), showed that the specimen consists of 90% of well-rounded equigranular quartz-grains (0.5 mm.) and 10% of chert-grains of the same size. The grains are not cemented, but merely surrounded by limonitic films. Reinhard concluded that the properties of the sandstone examined are in favour of wind transport. The sandstone is associated with compact ankerite (Nh. 129). These results confirm the views advanced above which are based on field-geological evidence.

It may be added here that 18 Tertiary sandstones from the west coast area, of Ta-b and Te age, were examined microscopically by Reinhard and compared with sandstones of assumed pre-Tertiary age, occurring in connection with radiolarian cherts and ophiolites. The Tertiary sandstones appear to be rather richer in chert-fragments than those of the pre-Tertiary Danau Formation. Other lithological differences were not noted. In both instances the cement is usually siliceous-argillaceous, sometimes calcitic. Apart from the predominant quartz-grains and subordinate chert-fragments, feldspars are of frequent occurrence, and among these antiperthite is not uncommon. Minor constituents of sporadic occurrence are micas, chlorite, garnet, zircon, tourmaline, apatite, rutile, leucoxene and iron-ore.

The Eocene erosional material was probably derived from the large pre-Tertiary uplifts in the Labuk and Segama area, as is shown by the arenaceous development and the considerable thickness of the Eocene sediments between these

two pre-Tertiary uplifts. On the Segama pre-Tertiary, variegated Eocene sandstones are found; in the northern section of the country the Eocene is in *reef facies* (Banggi Island).

An Eocene basin is indicated in the Sandakan-Kulapis-Lokan-Milian area; it was probably connected with a basin in the southern central part of North Borneo (Talangkai-Sapulut-Sibuda area) and on the west coast. In the last-mentioned areas it has, so far, not been possible to separate the Tertiary a + b from the overlying Tertiary e.

The water in the various Eocene basins apparently never reached any considerable depth. Shallow epi-continental basins subsided and simultaneously were filled up with predominantly arenaceous sediments. No geosynclinal basins had been formed.

Evidence of diastrophism after the deposition of the Tb and before Te was found in the Kulapis and in the Segama areas. In other places no indication of folding is found at this stage, though epeirogenic movements are evident.

The Kalabakang shales, whose lithological character is summarized in Table II, are covered by sediments of Te age. Reinhard (1924) assumed an Eocene age of the Kalabakang shales, though without palaeontological evidence. The series occurs in phyllitic facies in the upper reaches of S.Tiagau (Kalabakang), and here it has much in common with the Slate Formation of the Sapulut region. Therefore it may be compared also with this pre-Tertiary formation. Thus the age of the Kalabakang shales is uncertain.

b. *Tertiary* e_{1-4} (approx. equiv. Aquitanian, uppermost Oligocene)

Deposits of Te age transgressively overlie the pre-Tertiary in the northernmost, eastern and southern-central parts of the Colony of North Borneo. These sediments cover a much larger area than those of Tb age and often show an important thickness; they are predominantly arenaceous, locally argillaceous (Klias Peninsula) and tuffaceous-argillaceous (Dent Peninsula). The facies is indicative of a widespread shallow sea during Te times.

Tertiary e has been deposited in great thickness in two main basins that are separated by the pre-Tertiary belt stretching from the NW. to the SE. corner of North Borneo.

One basin was formed on the present NE. coast and another large one in the western, central and south-eastern parts of the country. The latter was connected with the Sarawak-Brunei basin to the west and with the Tarakan basin to the east. The two basins of North Borneo were connected in the Kudat area, along the Kinabatangan Valley, which had the character of a channel, and probably also to the east of Simporna Peninsula. It is an interesting fact that in Te times the waters had free access right across North Borneo, and the important Tertiary basins of Sarawak-Brunei, Tarakan and north-eastern Borneo communicated via the Upper Kinabatangan-Kuamut region. This fact is supported by palaeontological evidence. The Te micro-foraminiferal faunas of the lower Kinabatangan-Labuk region compare fairly well both with the Miri and with the Tarakan assemblages. The basin on the present NE. coast of Borneo has been studied in detail. The reader is referred to the descriptions given in Table I.

Similar to Tb, Te is composed of limestone on Banggi Island and predominantly of sandstone on the mainland. It appears that on the NE. coast we have to deal with sediments deposited in the south-western marginal zone of a basin which was situated to the NE. of Borneo.

Data from the Dent Peninsula are included in Table I. This part of the north-eastern basin is assumed to have been connected in the region of the present Sulu Sea with the main Te basin of the Kinabatangan-Labuk area; but on the mainland both parts appear to have been separated by a pre-Tertiary spur stretching from the Segama River toward S.Kratam-Dewhurst Bay. The Te of the Dent Peninsula is characterized by strong volcanic activity. Probably corresponding tuffs and tuff-breccias are found at Sandakan and on Berhala Island, but unfortunately this well exposed coastal section has so far not been examined in detail.

The Te of the interior parts and the west coast could not be separated from the Tb. In this region a transgression at the base of the Te could not, so far, be observed, although the Te sandstones frequently alternate with red shales, which are regarded as being redeposited Eocene sediments or perhaps lateritic detritus derived from pre-Tertiary uplifts.

Palaeontological evidence for *redeposited Eocene* was obtained from the association of larger Eocene foraminifera, together with those of Te age at various localities on the Kudat and Bengkoka peninsulas and also at a locality NE. of the Segama pre-Tertiary uplift (Batu Selawak).

The deposits of Te time also often show *reworked pre-Tertiary material*, such as red cherts and ophiolites. In this connection it has to be mentioned

that the Te surrounding the pre-Tertiary Danau Formation is predominantly arenaceous (northern and central parts of North Borneo), whereas the Te in the vicinity of the pre-Tertiary Slate Formation (in the south-western part of the country and in Sarawak) is essentially argillaceous. It is mainly on the Klias Peninsula that the Te_{1-4} is developed in a marine shale facies and has been regarded here as an oil mother-formation. A shaly development has also been noted in the eastern part of the Dent Peninsula.

In the northern and eastern parts of North Borneo we may thus assume the presence of a widespread transgression at the base of the Te, while in places an unconformity could actually be observed. In the western part of the country the presence of this transgression is so far only suggested by the occurrence of allegedly redeposited Eocene sediments during Te time.

Coral limestones form the top of the Te_{1-4} formation on Klias Peninsula and in the Kinabatangan area and underlie an important unconformity.

c. *Tertiary e_5-f* (approx. equiv. Miocene)

The natural stratigraphical boundary of the younger than Eocene series in North Borneo has to be placed between Te_4 and Te_5-f, thus approximately between Aquitanian and Burdigalian.

The series of Te_5-f age are clearly distinguishable from the older formations, not only on account of their lithology and fossil content, but also by a marked regional unconformity and a lesser degree of folding. The subsidence of the basins was interrupted by diastrophism near the end of the Te stage. Part of the pre-Tertiary and the Tertiary sediments were folded and imbricated and subsequently eroded. The *maximum movement* appears to have taken place between *Te_4 and Te_5. This is the most important Tertiary orogeny of North Borneo.* It appears to have been connected with and followed by igneous intrusions (Kinabalu)and extrusions (east coast) which do not occur in the sedimentary cycle of Te_5-f age.

A glance at the geological map (Enclosure I) shows the *striking angular divergence in dip and strike* between the Te_{1-4} and the Te_5-f formations west of Labuk Bay, at Tangkulap in S.Milian and in S.Pinanga. The actual plane of unconformity, marked by conglomerates, has only been observed at a few widely separated localities as, for instance, in S.Kuamut, S.Pinanga, S.Sepulut and S.Tungku. *Limestones and limestone-breccias*, however, are quite common at the base of the transgressive Te_5-f formation, especially in the Kinabatangan Valley. It is in this area that the Gomantong limestone of Te_5 age (S. of Sandakan Harbour and famous for its caves with edible bird's nests) unconformably overlies a steeply folded sandstone series. This is also the age of the Supu limestone-breccia (E. of Lamag), whereas the underlying and more steeply folded Batu Puteh limestone is of Te_4 age. As early as 1913, limestones transgressively overlying the pre-Tertiary were observed by Stamm (Wanner, 1921) at Batu Tapadong in S.Segama; these limestones could now be determined as Te_5-f. On Banggi and Balambangan islands the development of the reef facies also continued during Te_5-f time.

Not only the limestones, but also sandstones, clays and shales, overlying the unconformity, contain large foraminifera, indicating shallow-water conditions. The fauna of a sandstone bed occurring 2 m. above the basal conglomerate of the Bongaya Formation in S.Kuamut at the locality Tabakau (see Enclosure VII), is diagnostic of Te_4-f_1. In S.Tungku on the Dent Peninsula, sandy calcareous clays, also directly overlying the observed unconformity, contain foraminifera of Tf age. The foraminiferal layers occurring beneath and above the unconformity have been of great value for the age determination of this important stratigraphical boundary.

Summarizing the above, we may say that in North Borneo there is ample evidence for the prevalence of shallow-water conditions before and after the important phase of diastrophism and subsequent period of erosion of late Te age.

The faunal difference between the formations of Te_1-e_4 and Te_5-f age in North Borneo is also marked by the *smaller foraminifera* (see pp. 18, 19). As is shown in Table I, the boundary Te_4/e_5 approximately corresponds with the one in Brunei-Sarawak between the pre-Miri and the Miri formations, and in the Tarakan basin approximately with the boundary between the middle and the upper parts of the Birang Formation.

It is seen from the map that the Te_5-f basin in the north-eastern part of North Borneo was connected through the Kinabatangan Valley with a basin of the same age in the interior (rivers Kuamut, Pinanga, Sapulut, Sarudong, Kalabakang), which again communicated with the Tarakan basin. The sediments of the north-eastern and interior basins mainly form an alternating and very well-bedded series of sandstones, clays and shales with much

carbonaceous matter; locally limestones and coal seams are interbedded. The Te_5-f formation in these basins reaches a maximum thickness of 5,000 metres. The character of the sediments may, broadly speaking, be called paralic; thick argillaceous series which might suggest deeper water during the sedimentation, were not observed. It may thus be assumed that in north-eastern North Borneo and in the interior of this country during Te_5-f time a strong subsidence kept pace with strong sedimentation. The coaly leaves, often very well preserved, indicate that dry land was not too distant and was probably formed by the pre-Tertiary uplifts north and south of the Kinabatangan Valley (Miocene Kinabatangan channel).

d. *Pliocene and Pleistocene*

Tertiary formations younger than Tf, i.e. younger than Miocene, could be studied only on Dent Peninsula, Balambangan and Mangalum islands and on Klias Peninsula. On Dent Peninsula the marine and mainly argillaceous shallow-water facies of the Te_5-f is followed in Pliocene time by a predominantly paralic facies, which is in general lignitic and argillaceous. Strongly carbonaceous beds often alternate with clay beds, which fact is indicative of repeated fluctuations of the sea. The top part of the Dent Peninsula stratigraphical sequence is again formed by marine sediments, i.e. the Togopi Formation, which is developed in a reef facies and contains a rich fauna of foraminifera, gastropoda, lamellibranchiata and corals. The Togopi Formation has been regarded by the field-geologists and micro-palaeontologists as a Plio-Pleistocene series. The thorough examination of the molluscan fauna by L. R. Cox (1948), however, has shown that it is of Pliocene or even Upper Miocene age.

On Balambangan Island a facies similar to the Togopi Formation and probably of the same age is known to overlie the pre-Tertiary transgressively. It is remarkable that on Banggi and Balambangan islands all stages of the Tertiary are developed exclusively in reef facies. Judging by the persistent near-shore facies and the reduced intensity of folding in the Tertiary beds of this region it would appear that *shelf conditions* existed here during the whole of Tertiary times and that the pre-Tertiary basement was continuously at shallow depth.

On Mangalum Island a marly sandy formation, identified palaeontologically as the equivalent of the Togopi Formation, was encountered in core-holes and appears to lie unconformably on beds of Te_4-$_5$ age.

We may finally remark that North Borneo is at the present time fronted to the NE. and to the SE. by deep sea basins, the Sulu Sea and the Celebes Sea; it is assumed that bathyal sediments are being formed in these basins. Tertiary deep sea basins apparently do not occur in North Borneo, although in places near the NE. coast a stratigraphical sequence of Tertiary sediments with a total thickness of well over 10,000 metres is known. In North Borneo, therefore, it appears that sedimentation kept pace with the submergence of the basins.

3. Brine Springs, Mud-Volcanoes, Oil- and Gas-seepages

Salt-water seeps and *springs* are of frequent occurrence in the areas of the variegated sandstone-shale series of Ta-e age though they are not entirely restricted to these formations. In some parts of North Borneo they are sparsely scattered, but in the Kinabatangan region salt-water " licks " and springs are very numerous. They are known as *tagai* to the natives, a word which is also applied to mud-volcanoes. Most of the springs have no unusual character, being small muddy openings in the jungle generally much frequented by all kinds of game.

The salinity of the water can reach 32 grams per litre, but it varies rather widely from place to place and with the seasons, becoming lower in wet weather. A number of the brines have been analysed. Sodium chloride is the principal salt; minor amounts of sulphate, carbonate and bicarbonate are present. In one sample traces of iodine were recorded. A few of the brine springs in the interior, as, for instance, that at the locality Tagai, SW. of Kuamut, are used for salt production. In the southern adjacent Sarawak-Netherlands Borneo border region numerous brine springs are known from similar formations and are used for salt production.

In the discussion of the unusual colours of some Lower Tertiary formations, the occurrence of brine springs has been cited as evidence for the deposition of the accompanying rocks in a strongly saline environment.

An unusual feature is the occurrence of a number of *mud-volcanoes* in the north-eastern part of North Borneo and of a few in the south-western part of the territory.

The north-eastern mud-volcanoes (see Plate XIX) are found on the islands off the Sandakan Peninsula, in the lower Kinabatangan-Segama region and in the Tabin-Tungku area on the Dent Peninsula. They are in rough alignment along a narrow zone 150 km. long. The largest mud-volcanoes in the period 1936–1939 were those of Ulu Sapa Puti Rasang in the Kinabatangan area and of Ulu Tabin in the Dent Peninsula.

Apart from the mud-volcanoes on the low and gently sloping islands of Boaan, Liheiman, Silingaan, Langgaan, Bakungan Besar and Kechil and Nunuyan to the north of Sandakan, these large *tagai* have not been reported before. Most of them were traced on information obtained from aerial photographs; only a few are known to the natives.

The large mud-volcanoes in the jungle of north-eastern North Borneo form circular or elliptical openings up to 180 m. in width, occasionally surrounded by a belt of brackish-water plants. They are situated on the top of gently sloping hills with mud-streams on the flanks. The clearings are generally slightly convex plains covered with dried salty mud, white sand and a number of boulders of bed-rock. Approximately in the centre of the clearing is a muddy area with one or more cones or basins which produce inflammable or non-inflammable gas or both, also salt-water, mud and rock boulders. Their activity is intermittent. At long intervals, which may be of several months or even years duration, violent explosions occur which are preceded or accompanied by local earthquakes. Masses of mud and large rock boulders are then ejected. The boulders are sometimes cracked like volcanic bombs and may have a baked appearance. The mud, too, which is usually bluish-grey, may have a baked appearance and purplish-reddish colour. At the Tagai Ulu Tabin many crystals of pyrite and calcite are found in the mud.

The life of the mud-volcanoes is sometimes fairly short. After remaining active for several years they may gradually cease to function and become again overgrown by jungle until the next explosion occurs. According to information obtained from natives and from aerial photographs, the mud-volcanoes of the Segama-Kinabatangan area may disappear at one place while new cones start to function in the surrounding country.

The emanating gas consists largely of methane (CH_4) with admixture of nitrogen (N), but usually without carbon dioxide (CO_2). Neither oil-smell nor oil has been noted. The issuing brine has the same composition as that of the ordinary salt-water seeps in the Tertiary formations. The boulders which are brought up, together with the mud and scattered around the volcanoes, vary from walnut-size to a cubic metre. They consist predominantly of clay, shale, marl, sandstone and sandy limestone, which are derived from the Tertiary formations. The pre-Tertiary Danau Formation is sometimes also represented by characteristic rock types, such as chert, amygdaloidal spilite, serpentine and gabbro. Moreover, crystalline schists (e.g. hornblende-schists) are reported. Peculiar porous volcanic rocks, found on Liheiman Island, Tagai Rasang and Tagai Tabin, sometimes ascribed to the Tertiary, Quaternary or even to recent times by some geologists, could microscopically be determined as weathered spilites and variolites belonging to the ophiolitic suite of the Danau Formation. In the central part of these porous rocks the vesicles are filled with calcite and albite. This structure and the mineral combination are characteristic for the amygdaloidal spilitic rocks. No Tertiary andesites or Quaternary volcanic rocks have so far been collected from the material brought up by the mud-volcanoes.

As brine springs and mud-volcanoes are favourite meeting grounds for all kinds of wild life, plenty of tracks are seen converging toward them. Some of the elephant tracks can be traced from a distance of well over 10 km. and form deeply entrenched jungle highways. The few natives who have witnessed the violent explosions and nightly flares of a mud-volcano, but who, a few years later, could not find any trace of it, believe that they were supernatural phenomena. The geologist, however, who has to admit their natural origin, can offer no satisfactory explanation for this very striking but puzzling manifestation.

The assumption that the eruptions have their origin within the sequence of Tertiary sediments, is obviously not satisfactory, as in this way the abundant occurrence of rocks of pre-Tertiary age could not be explained. In the Segama region the igneous and metamorphic rocks might originate from the Tertiary Tungku conglomerate; but in the Kinabatangan area sedimentary deposits of such rocks are unknown. Also the assumption of pre-Tertiary thrust-sheets within the Tertiary series is highly improbable. It is legitimate, however, to assume the combination of methane, nitrogen and salt-water to be derived from the Tertiary sediments. This association is of common occurrence within the sediments of Ta-e age of the adjacent areas.

A *volcanic origin* was assumed by Reinhard (1924) and other geologists. However, although methane may occur as a volcanic gas, solfataric activity is entirely missing in the mud-volcanoes, and hydrothermal phenomena are restricted, as far as has been observed, to Tagai Besalag Nemud in the Dent Peninsula. Again, the normally recognized volcanic manifestations are found, not in association with the mud-volcano zone, but following a different direction. The trend of the true volcanic zone is NE.–SW., following the line Sulu Islands-Tungku-Simporna Peninsula. There the Neogene volcanism was of a highly explosive character, and transitions to the assumed post-volcanic mud-volcano type are unknown. A further objection against the volcanic origin of the mud-volcanoes is seen in the composition of the ejected boulders.

As was mentioned above, the gas and salt-water emanating from the mud-volcanoes very likely originate from the Tertiary sediments. We can exclude almost certainly an origin from the highly disturbed pre-Tertiary Danau Formation. Nowhere have mud-volcanoes been located in areas occupied by pre-Tertiary, although many of them appear to be in some connection with pre-Tertiary uplifts. It is possible that the zone of mud-volcanoes follows an undulation of the pre-Tertiary basement.

The zone of mud-volcanoes in north-eastern North Borneo runs obliquely to the Tertiary structures, except for the extreme N. end of Boaan-Liheiman. It can hardly be connected with a fault of such regional extension without some sign of such a fault being visible. The phenomenon cannot be explained by the Tertiary tectonics; it is certainly of a deep-seated origin.

As mentioned above, the mud-volcanoes are not randomly distributed in the north-eastern part of North Borneo, but are aligned in a narrow, curved zone 150 km. long. This arc appears to be intimately connected with the origin of the mud-volcanoes. As is shown on the 1:2,500,000 Structural Map (Enclosure II), the zone of the mud-volcanoes is *concentric with the contour lines of the Sulu Sea*, situated on its concave side. It is possible that the mud-volcanoes are connected with the comparatively recent formation of this deep-sea basin.

In the Moluccas analogous mud-volcanoes occur in Pliocene and Mesozoic strata. They often occur on Pliocene dislocation lines and are confined to areas with uplifted reefs. Their arrangement around the Banda Sea and following the Timor-Ceram arc was noted by F. Weber (unpublished report), who considered the mud-volcano phenomenon of the Moluccas as being in connection with recent orogenetic movements of the arc surrounding the Banda Sea. Heim (1942) regarded these mud-volcanoes as diapyric perforations of the basement caused by recent orogenetic movements. The mud-volcanoes of north-eastern North Borneo may also be diapyrs of deep-seated origin, but their mechanism has not yet been explained.

The mud-volcanoes on the west coast have a different character. They are restricted to the Klias Peninsula and adjacent islands. On the hilly ridge of the peninsula a large number of them can be seen, sometimes in groups. They produce mud, salt-water and methane gas; occasionally oil-films or oil-smell can be detected near the vents. Igneous rock boulders are not reported. In some cases small cones have been built up and some have given rise to extensive mud-flows. Exceptionally violent eruptions have sometimes taken place, such as the eruption at Tanjong Nosong in 1939 and the explosion which occurred on Pulau Tiga in February, 1941, when the gas ignited and burned for weeks. A large amount of mud was ejected in this latest eruption and the jungle for a considerable distance around the vent was overwhelmed by the mud and destroyed. Worthy of note are the new islands which have appeared off the Klias coast, probably as a result of submarine mud-volcanoes. One island, since disappeared, arose in the sea off Lumbidan in 1897 (Schmidt, 1904) and one in the Nosong shoals in 1935.

The west coast mud-volcanoes occur in oil-bearing formations of Te age; they follow Tertiary anticlinal crests and seem to be of purely sedimentary origin, similar in type to those of Burma, Russia and Roumania and connected with the release of pressure of gases produced in the underlying beds.

With one exception (Sebatik) all genuine *oil-seepages* found in North Borneo occur on the west coast (Sequati on Kudat Peninsula, Mangalum Island, Klias Peninsula) and are derived from formations of Te and of Plio-Pleistocene age. From the west coast districts also many gas-seeps are reported, some of which have strong oil-smells (e.g. P. Mantanani).

In the east coast districts ordinary *gas-seepages* have been found in S.Paitan and on the Dent Peninsula. In this easternmost part of the country, an oil-smell has been noted in gas struck in a core-hole.

Several wells were drilled in North Borneo before the recent exploration period (1935–1939). Some of them found oil, but none ever gave commercial production (for details see p. 6). Core-drilling is in progress on Mangalum Island, and further exploration may be carried out in the near future on the Klias and Simporna peninsulas. Five analyses of crude-oils are listed in Table III.

TABLE III. ANALYSES OF CRUDE-OILS FROM NORTH BORNEO

	1 Well No. 1 Tindak Klias Peninsula	2 Well No 2 Tindak Klias Peninsula	3 Sequati seepage	4 Mangalum seepage	5 Mangalum corehole 26B
Sp. Gr. at 15°C.	·9154	·8417	·972	·964	·832
Flash point				126	Below 30°C.
Pour point	Below 15°F.	Below 15°F.	Below 15°F.	Below 5°F.	Below 15°F.
Viscosity at 30°C.	1·39°E.	1·02°E.	7·21°E.	15·44°E.	1·03°E.
Water content	·25%	nil	trace	·2% vol.	·3%
Wax content	Negligible	·024%	Negligible	Negligible	—
Asphaltenes (insoluble in ethyl ether)	0·003%	trace	·03%	—	—
A.S.T.M. Distillation:					
I.B.P.	201·5°C.	112°C.	220°C.	241°C.	77°C.
10% off to	230°C.	131·5°C.	255°C.	277°C.	113°C.
20	243°C.	142°C.	277·5°C.	292°C.	133°C.
30	254·5°C.	153·5°C.	295·5°C.	313°C.	149°C.
40	263°C.	168·5°C.		333·5°C.	167°C.
50	274·5°C.	188·5°C.		352·5°C.	192°C.
60	287°C.	216°C.		370°C.	218°C.
70		244°C.			249°C.
80		270·5°C.			282°C.
% distillling to 125° ..		5·0			16·5
150° ..		27·5			30·5
175° ..		43·5			43·5
200° ..		55·0			53·0
225° ..	7·5	63·5	·5		62·5
250° ..	26·0	72·5	8·5	2·5	70·5
275° ..	50·5	82·0	19·0	9·0	78·0
300° ..	68·0	89·0	33·0	23·5	84·0
325° ..				36·0	
350° ..				49·0	
371° ..				60·5	
Residue %	31·5	10·5	66·5	39·0	15·5
Loss %	0·5	0·5	0·5	0·5	0·5

4. Tertiary Tectonics

Tertiary movements of Eocene age cannot be separated from the folding which had its culmination in late Te times and is responsible for the present tectonic picture. The late Te orogeny not only strongly affected the Tertiary strata, but also the previously folded pre-Tertiary basement and created an intricate pattern of in-folding. Two observations by Hotz and Niethammer in the well-exposed west coast area are very instructive in this respect: in the section of S.Toaran, south of Marudu Bay, Hotz has observed a SW. dipping Tertiary series with two intercalations of pre-Tertiary rocks. This is an interesting example of small-scale imbricate structure (see Fig. 3, sections 1 and 2). In the Langkom-Kota Belud area, adjoining to the west, Niethammer has found that pre-Tertiary is not only exposed as the cores of Tertiary anticlines, but has actually been folded together with the Tertiary sediments (see Fig. 3, section 3). Farther to the south, in the Tampasuk district, Tertiary and pre-Tertiary are so intensively folded and interlocked that they cannot always be separated. These observations show that the *Tertiary sediments are not sheared off from the pre-Tertiary basement and folded independently in themselves, but that the Tertiary and part of the pre-Tertiary have undergone the same compressive folding and shearing.*

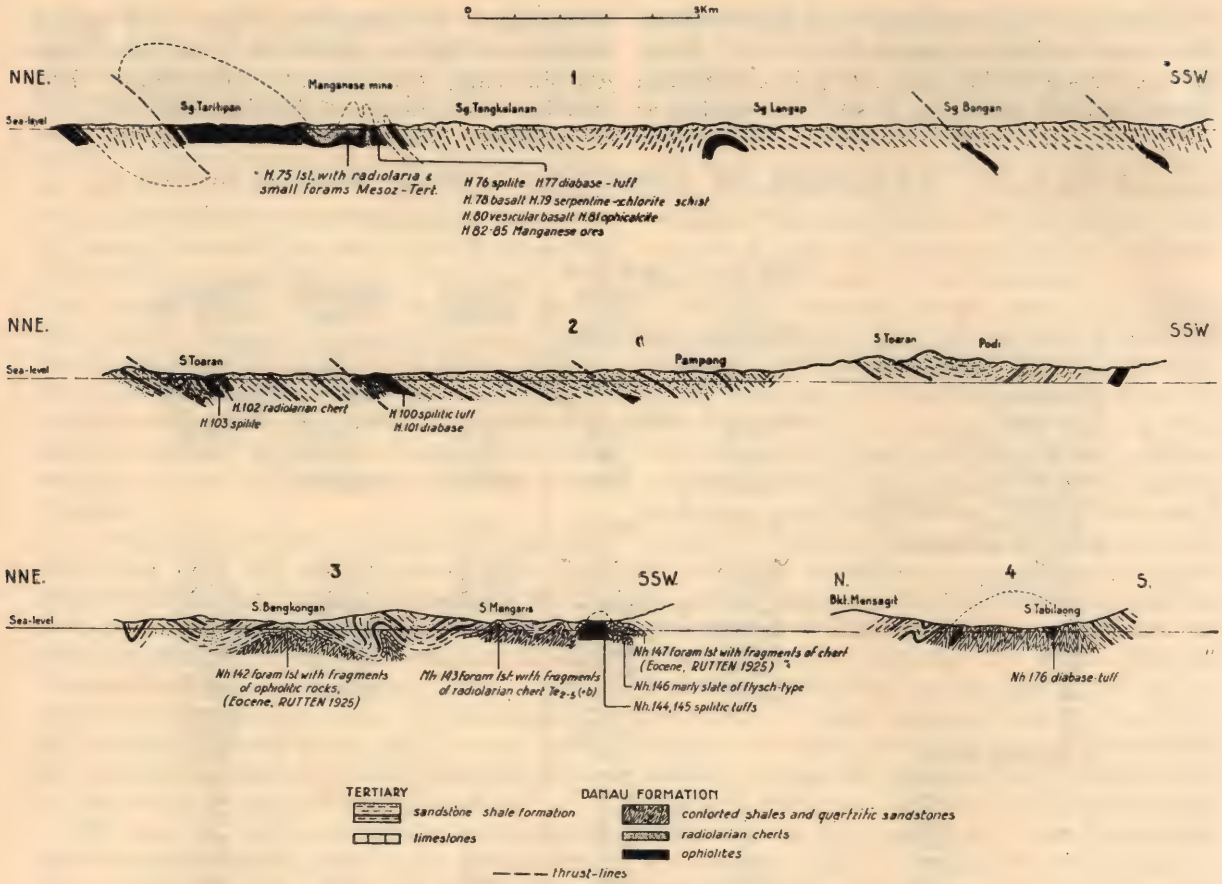


Fig. 3. Cross-sections through the area SE. and SW. of Marudu Bay
By W. Hotz and G. Niethammer

In the Crocker Range (1,500–2,000 m.) and its foothills along the west coast the Tertiary is mainly isoclinally folded. Hotz and Niethammer drew attention to some conspicuous changes in the trends of the west coast district. Along the coast and in the Trusmadi Mountains the strikes are mainly NNE., while in the intermediate Pegalan Valley between Keningau and Kinabalu only WNW. strikes occur. Hotz regarded the SE.–NW. direction as older and autochthonous, and explained the folds with a SW.–NE. strike as a thrust-sheet, with the Trusmadi Mountains as root-zone and Pulau Gaya near Jesselton as its front. This interpretation was undoubtedly inspired by the revolutionary progress of alpine tectonics in those years (1914–1915). However, no thrust planes were observed which would support the assumption of a tectonic displacement of Tertiary strata over a distance of more than 100 km. Moreover, to the west of Tambunan, a convergence of the two trends can be traced, and consequently the west coast tectonics have to be explained without assuming such large-scale thrusting. As a result of the progress made in mapping, the regional relationship is clearer now than it was in 1915 (see Structural Map, Enclosure II). The bending of the Tertiary folds around the edges of the pre-Tertiary masses is particularly clearly demonstrated. The uniform NNE. trend of the Crocker Range prevails from the Padas area as far as Jesselton. At Tuaran it bends round to the NE., and to the north of Kota Belud all the Tertiary structures swing abruptly to the east and follow the northern edge of the pre-Tertiary there (cf. Enclosure I).

Similar changes of trends are recognizable in the SE. part of North Borneo, where the NW. strike of the Sarudong-Kalabakang region passes into a NE. strike in the Kuamut-Kinabatangan

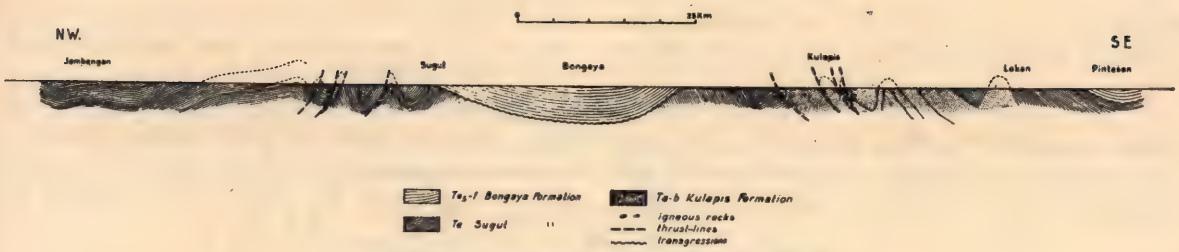


Fig. 4. Section along the NE. coast of North Borneo
After W. F. Schneeberger and E. Wenk

area. Here again, the obvious explanation is that the pre-Tertiary blocks have directed the folding, either as moving masses or as rigid frames.

With a few exceptions the sediments of the Tertiary a-e_4 in North Borneo are isoclinally folded and imbricated. Prominent individual anticlines hardly exist. The sections (see Figs. 3 and 4) show the type of structure, and Fig. 5 presents the detailed tectonics at Tg. Lokpadsang on SW. Kudat Peninsula as observed by Niethammer. The diastrophism, taking place after the deposition of the Ta-e_4 and before the late Te denudation and ensuing transgression of the Te_5-f, was much more intensive in North Borneo than in coastal Sarawak and along the coast of Netherlands Borneo. But the same intense folding type was observed in Central Borneo, to the south of the Colony of North Borneo, by Schneeberger and Bächlin. Pre-Tertiary and Tertiary a-e were folded almost to the maximal compression, and this may also account for the very peculiar structures of the Te_5-f formation.

The Tertiary Te_5-f is preserved in some flat synclinal basins, a good example of which is the Bongaya syncline in Labuk Bay (see Fig. 4), where this phenomenon was studied first. Other synclines of similar shape were discovered in the interior, but their peculiar shape was only fully revealed by aerial photography. Photogeological maps of the almost circular basins of S.Malua and of S.Bangan south of Tangkulap, are shown on Figs. 6 and 7 (see also Enclosure VII). The Malua synclinal basin has a diameter of 13 km.

It seems impossible to explain such structures by tangential compression alone, without taking into consideration local downward movements. To the SW. of the Bangan synclinal basin a regularly shaped, elliptical plutonic body of similar dimensions occurs (Gunong Rara, see Plate XX), which appears to be of Tertiary origin. It is logical to ascribe the synclinal troughs to a compensating subsidence of the magmatic basement.

Only in the Kinabatangan Valley, between Pintasan and Kuamut, is the Tertiary e_5-f steeply folded. This, apparently, was caused by compression between the pre-Tertiary Segama and Labuk blocks. In the head-waters of S.Pinanga (tributary of the Milian) gentle folds occur again, such as the Inarad anticline. This zone of gentle folding continues into the head-waters of S.Kuamut, and appears to be connected with the regular structures found in the upper reaches of S.Kalabakang and in the Tambalunan-Sarudong-Silimpopon region in the south-eastern part of the country.

On the Dent Peninsula t_e Neogene is laid in gentle normal folds running parallel to the volcanic arc Simporna Peninsula-Sulu Archipelago mentioned below. There are indications in this district that sedimentation and folding proceeded simultaneously from the Miocene up to the Quaternary. The last gentle folding (post-Togopi) is very recent (? Pleistocene-Quaternary).

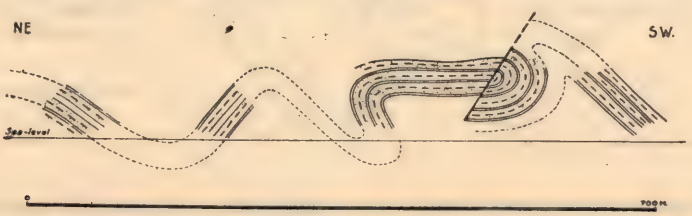


Fig. 5. Section along Tg. Lokpadsang, W. coast of the Kudat Peninsula
Observed by G. Niethammer in a sandstone-shale complex

Fig. 6. Photogeological map of the synclinal basin of S.Malua (Kinabatangan)
Photogeological interpretation by H. Boissevain

In the extreme south-west of the country, in the Lawas-Bol area, fault tectonics seem to prevail, but nothing further can be usefully said on this subject as this area has not yet been thoroughly explored.

5. Major Tectonic Features and Regional Relationships

Several authors (Van Es, 1920, Brouwer, 1925, Staub, 1928) who discuss the geological structure of the East Indies, show the important Tertiary trend lines of Sarawak and the Netherlands border area (Central Borneo) crossing North Borneo in a NNE. direction and extending via Kudat-Bengkoka

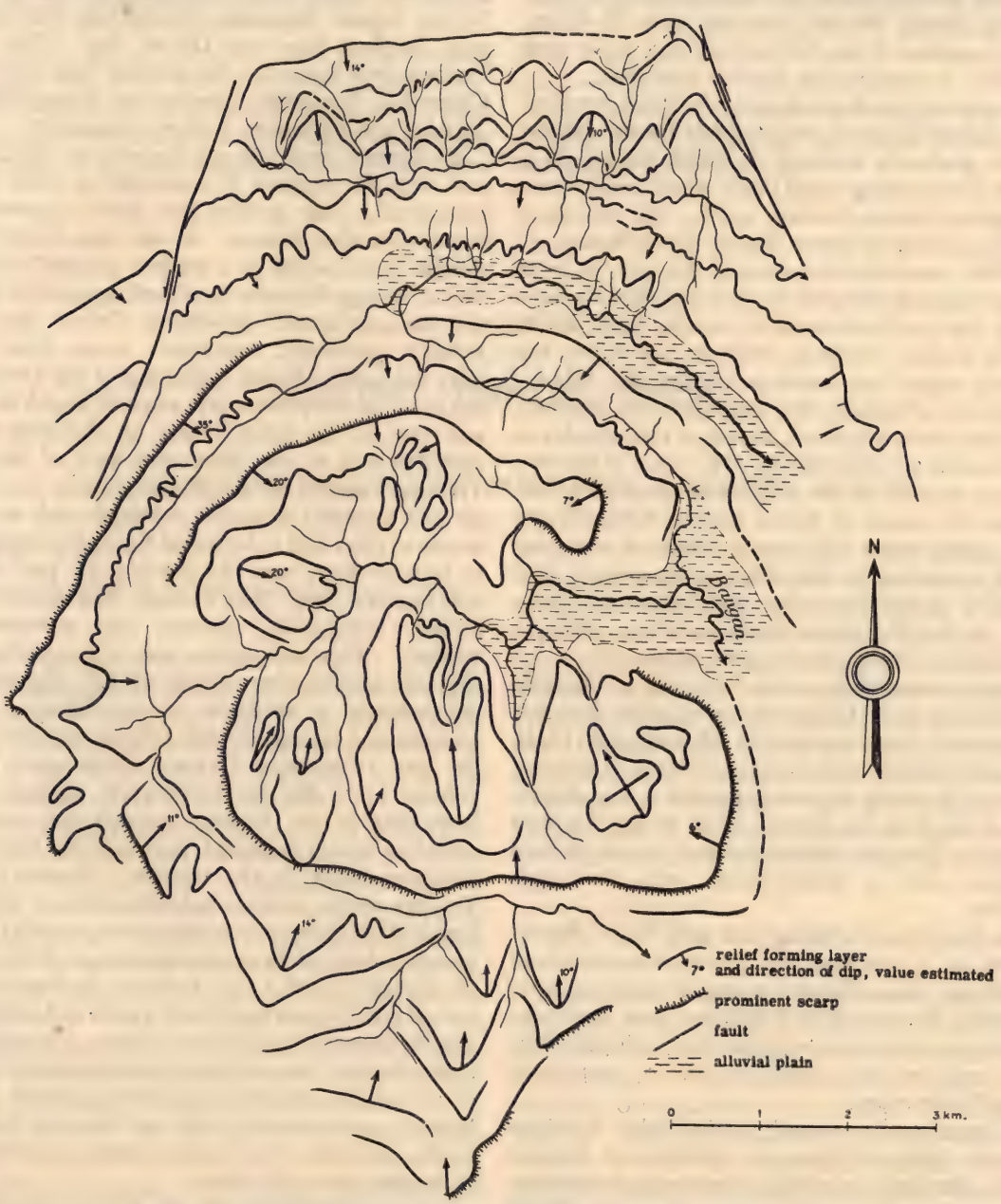


Fig. 7. Photogeological map of the synclinal basin of S.Bangan (Kinabatangan)
Photogeological interpretation by H. Boissevain

peninsulas and Banggi Island toward Palawan and Mindoro in the Philippine Islands. This assumed structural line, indeed, follows a well-pronounced ridge and is a morphological feature. It has, however, nothing to do with Tertiary tectonics. On the Kudat and Bengkoka peninsulas the line crosses the Tertiary strike at right-angles, and its northern prolongation, the conspicuously shaped Palawan Island, 400 km. long and only 20–40 km. broad, consists of pre-Tertiary igneous rocks with few relics of transgressive Eocene limestone.

The general north-north-easterly trend prevalent in the Brunei-Sarawak-Netherlands Borneo border area, is gradually replaced in North Borneo by a system of branching trend lines, which bend round the edges of the pre-Tertiary uplifts. The structural map (Enclosure II) shows that in North Borneo all the NNE. structural elements of the late Te cycle of diastrophism swing to the east and, having once passed the pre-Tertiary belt, resume their north-easterly strike. However, they do not follow the Palawan ridge nor converge toward the Sibutu-Basilan arc of islands, but run right into the Sulu Sea. The folds are cut off, almost at right-angles to the direction of strike, by the NE. coast of Borneo, which is fronted by the 3–5,000 m. deep Sulu Sea. Off the NE. coast of North Borneo Schneeberger noted conspicuous NE.-running lines of reefs and shoals, occurring in the direct north-eastern prolongation of anticlinal axes observed on the mainland. In the Philippine Islands of Paney, Negros and Cebu a NNE. strike is again noticeable.

These various facts are in favour of a comparatively recent (post-Te) development of the Sulu Sea and support the views held by Molengraaff (1922), Umbgrove (1934) and Kuenen (1935). They are, however, a strong argument against a *Zwischengebirge* in the Sulu Sea (Staub, 1928) during the most important Tertiary diastrophism of North Borneo and are also in disagreement with Brouwer's theories.

The Sulu Sea is a broad and deep basin characterized by a comparatively even floor at about 3–4,000 m., steep sides and a strong positive gravity anomaly. Kuenen (1935) explains such basins by assuming a regional downward force whereby they have sunk *en bloc* along flexures or step-faults around their edges.

As mentioned previously, the circular, synclinal Miocene basins of Bongaya, Malua and Bangan may be the result of similar downward movements on the mainland, though on a smaller scale. If this assumption be correct, they should also form gravity highs, similar to the deep sea basin mentioned. Unfortunately geophysical prospecting has not yet been carried out in the area under discussion.

The following structural zones border the southern part of the Sulu basin and appear to be in some genetical relationship with it:

1. *The belt of pre-Tertiary rocks of the Danan Formation* comprising Palawan Island, Banggi Island, Kudat Peninsula, Tampasuk and Labuk area, Segama area and Darvel Bay. This pre-Tertiary belt separates the present Sulu from the China Sea. It existed in some form throughout the Tertiary and its history is most interesting.

In Eocene times the pre-Tertiary of the Labuk and Segama regions is assumed to have been temporarily and locally dry land, exposed to weathering and erosion. It was also partly submerged and covered by a shallow sea (reef facies in Kudat-Banggi-Palawan area) and lagoons in which the epi-continental, red-brown Darvel Bay and Kulapis sediments, containing much fossil salt, were deposited. In the beginning of the Tertiary e the basin on the present NE. coast of North Borneo and that in the interior and on the west coast subsided and at the same time part of the pre-Tertiary, covered by Eocene sediments, was lifted up and supplied erosional material such as fragments of chert and redeposited Eocene foraminifera in beds of Te_{1}-$_{4}$ age. In the late Te, part of the pre-Tertiary and the Tertiary sediments were folded, imbricated, uplifted and subsequently eroded. This orogenesis was accompanied by volcanic activity, especially in the SE. The severest deformation is confined to the Tertiary areas between and around the pre-Tertiary masses. After the late Te erosion, Tertiary strata again transgressed upon the pre-Tertiary (P. Banggi, Batu Tapadong in the Segama region) and the surrounding basins deepened, especially the important Neogene basin in the interior. However, pre-Tertiary uplifts existed, and these areas of dry land supplied the abundant carbonaceous material which occurs in beds of Te_{5} and younger age. Only along the Kinabatangan Valley between the Segama and Labuk pre-Tertiary uplifts did a deep and important depression exist from Tb to Tf time. Through this Kinabatangan channel, which has the characteristics of a trough, the basin in north-eastern North Borneo communicated with the Sarawak basin up to Te, and with the Tarakan basin, via Kuamut-Sarudong, up to Tf times.

It is very likely that the pre-Tertiary belt existed as an arc of islands up to the end of the Miocene,

and that simultaneously with the subsidence of the Sulu basin the main part of North Borneo became dry land.

2. *The volcanic arc*, which, on the east coast of North Borneo, comprises the Simengaris region, P. Sebatik, Simporna Peninsula, P. Timbun Mata, P. Gaya and the southern part of Dent Peninsula, and, of the Philippine Islands, P. Sibutu, P. Tawi-Tawi, Jolo, Basilan and Mindanao. This remarkably straight line of volcanic islands and peninsulas separates the Sulu Sea from the Celebes Sea. Parallel with it run the Miocene-Pliocene structures of the Dent Peninsula and a system of coral reefs and shoals in its north-eastern prolongation. The volcanic arc is discussed in more detail in Chapter VI.

3. *The zone of mud-volcanoes*, comprising the islands of Boaan, Liheiman, Silingaan, Langgaan, Bakungan Besar and Kechil and Nunuyan to the north of Sandakan, and on the mainland the Lower Kinabatangan-Segama-Tabin-Tungku region. As mentioned before (see p. 24), the zone of the mud-volcanoes in north-eastern North Borneo appears from a regional point of view to be related with the formation of the Sulu basin.

This outline may show that many geological features of North Borneo are closely related with the history of the Sulu Sea.

CHAPTER VI

Tertiary Igneous Rocks

A. VOLCANIC ROCKS OF SIMPORNA AREA, SE. COAST

Geology

1. *Geographical and Geological Positions of Outcrops*

The locations of the Tertiary volcanic rocks of North Borneo are shown on Enclosure I. The most important outcrops are to be found in the SE. of the country, mainly in the Simporna Peninsula, in the islands east of Simporna and in the southern half of the Dent Peninsula.

When this distribution is viewed in relation to the more limited field of the geology of North Borneo, it appears to be eccentrically situated and isolated. However, when their regional geological relationships are considered (see Structural Map of North Borneo and adjacent Philippine Islands, Enclosure II), these localized occurrences gain in significance. They are important links in the 1,200 km. long chain of Tertiary volcanic rocks, which extends from Mindanao (Philippine Islands) across the Sulu Archipelago (Basilan, Jolo, Tawi-Tawi, Sibutu) to the SE. of North Borneo, and which can be followed from there in a SW. direction along the coastal area of the Tidung Districts down to the upper courses of the S.Mahakam and the S.Barito in Central Borneo, and probably even still farther toward West Borneo. This geologically significant linear feature is not straight, but clearly consists of two arcs, the convex sides of which face SE. The two arcs intersect in the territory of the Tidung Districts and Bulungan in Netherlands Borneo. In this respect the zone of Tertiary volcanic rocks resembles the arc-shaped chain of islands extending from the Philippine Islands across the Japanese islands towards the north-east corner of Asia. In fact the volcanic zone of the Sulu Archipelago and of Borneo forms the south-western prolongation of the important East Asian volcanic arcs.

2. *Mode of Occurrence and Nature of the Volcanic Activity*

Because volcanism in North Borneo died out as long ago as the Miocene times, its products have now been deeply eroded and are covered with dense jungle. Volcanic structures are therefore not easily recognizable in the field. The morphology of these regions could be analysed most rapidly by the use of air photographs, but for obvious reasons the volcanic regions have not been included in the air mapping carried out by the Shell Group.

Good outcrops of the volcanic series in North Borneo can be found in some streams and rivers, such as the S.Tawau, S.Klumpang, S.Silibukan, S.Tabanak, S.Mungkuou (S.Rashleigh of the sea chart) and S.Tungku. The best exposures are on the island of P. Gaya, NE. of Simporna, where steep cliffs built of volcanic material rise from the sea.

At various spots in the Simporna Peninsula, for instance in the regions of the S.Tawau (Mt. Magdalena) and the S.Klumpang, rather extensive lava streams were observed by Reinhard and Spiegelhalter. In the head-waters of the S.Biag Tagai, which is a small tributary of the S.Tungku, an andesite mass was observed, which probably was the pipe of a composite volcano. Dome-like structures and dykes of andesite have been found in the S.Mungkuou, the S.Babagkang (tributary to the S.Sebahat, Dent Peninsula) and in P. Gaya. Stamm (Wanner, 1921, op. cit. p. 159) has observed that Bedakson Hill, in the middle course of the S.Segama, is an andesite plug which has broken through the andesitic tuff-breccia, clays and shales of the Tabanak layers (Te) and has hardened the latter at the contact.

Such coherent masses of andesitic rocks are found at various places in North Borneo, but more frequently the Tertiary volcanic formation consists of volcanic breccias, agglomerates and conglomerates which pass laterally into tuff-breccias and tuffs, and alternate with tuffs to tuffites, or with lava beds. All gradations are found, from volcanic breccias, derived from block-lavas, to volcanic agglomerates with round-edged to rounded andesite blocks and coarse volcanic conglomerates. The latter are of frequent occurrence, particularly in the Tabanak-Silibukan-Tungku region (Dent Peninsula), but also on the Simporna Peninsula. They consist of blocks (diam. 10 to 100 cm.) mostly of andesitic material but to a lesser extent of blocks of sedimentary, igneous and metamorphic rocks (sandstone, chert, ophiolitic rocks, crystalline schists, including in particular amphibolite and eclogite) embedded in a tuffitic cement rich in lapilli. Some of the angular to round-edged blocks show gaping clefts and cracks and have the appearance of volcanic bombs. Others, however, have assumed a well-rounded shape and are covered with a pitch-black dull to glossy crust. Owing to intercalated beds of tuffite and of sandy, sandy-clayey to marly sediments, which sometimes contain foraminifera, the volcanic conglomerate series may in some places show good stratification. In the S.Tabanak, embedded lignite blocks and pieces of silicified wood have been found.

The agglomerate and conglomerate series in the S.Tabanak and the S.Tungku reaches a thickness of 800 m. to 1,000 m., which decreases rapidly to the north-west and east. In the S.Sebahat and the S.Babagkang (6 and 13 km., respectively, NE. of S.Tungku) only thin beds of the volcanic agglomerate occur in the various horizons. There they alternate with clays rich in tuff and thin out toward the east and north-east. Furthermore, starting from the Tabanak-Tungku region, there is a gradual decrease in the size of the constituents of the pyroclastic series. The volcanic conglomerates are gradually replaced laterally by tuffite-breccia and tuffite. In the south the main area of occurrence of the series of rocks described cannot be delimited because the sea intervenes. In P. Gaya, north-east of Simporna, the pyroclastic series forms cliffs more than 100 m. high. Here it has the nature of a volcanic agglomerate which alternates with beds of lava and of tuff, the whole being traversed by andesitic dykes.

On the basis of the splendid outcrops of P. Gaya and of additional observations, it is possible to determine more precisely the nature of the volcanic action. The Tertiary volcanism was of a highly explosive type. The materials discharged were predominantly loose products, such as ashes and ejectamenta varying in size from that of lapilli to that of blocks, and lavas only to a lesser extent. Together with the bombs of vitrophyric to holocrystalline volcanic material, blocks of the Tertiary and pre-Tertiary basement were also ejected, but mainly the latter. The ejectamenta were deposited in the sea, as is proven by their admixture with sedimentary material, which locally contains foraminifera. Plant debris, swept out from the land, was also added. The volcanic material has been more or less reworked and redeposited. It is possible that a part of the loose ejectamenta had originally been deposited on the slopes of the volcanic cones emerging from the sea, and were then eroded, whereas the marine transgression did not take place till afterwards.

The centre of the volcanism in Dent Peninsula was in the Tungku-P. Gaya region; that of the Simporna Peninsula in the Tawau-Klumpang region, as is evident from the extrusive bed-rocks and is also shown by the gradual decrease in the size of the ejectamenta as one moves away from these centres.

Tuffites, in part foraminiferal, are also found in

the Sandakan Peninsula. It is problematic whether these occurrences were connected with the same volcanic eruptions in east and south-east North Borneo, or whether they originated from centres situated in the sea north of Sandakan. No Tertiary lavas or dykes have so far been found in the Sandakan Peninsula.

The geological arguments for a highly explosive type of Tertiary volcanism are also in line with some of the results of petrographic investigations: the dacite-andesite-basalt series is chemically a very Pacific association. The comparative examinations by Rittmann (1936) in particular have shown that the volcanism which produces Pacific magmas is as a rule highly explosive. Furthermore, the study of the reaction series biotite → hornblende → hypersthene + augite, established in the North Borneo volcanic rocks, shows that the magma must originally have had a high water-content (the stable phases being biotite and hornblende), but that in the course of volcanic action water-vapour and other volatile components escaped. The biotite and hornblende crystals, already separated off in the magmatic reservoir, were no longer in equilibrium with the magma, which had become poorer in mineralizing agents; they were resorbed, and pyroxene, ore and feldspar were formed instead. The fact that many examples of transitional stages of the reaction series have been preserved, leads to the conclusion that the magma reservoir rapidly discharged its gaseous components as well as crystallization products, as is the case with highly explosive volcanic action. The recent volcanism in the archipelago shows the same highly explosive character.

It may incidentally be observed that the presence of much loose, easily weathered volcanic material, frequently mixed with clayey-sandy sediments, will have a very favourable effect on the formation of agricultural soil. The tuffitic beds make especially fertile soils (Tawau, Tungku), of which so far only a very small part has been made arable.

3. *Age of Volcanism*

Field observations show that the andesitic rocks break through sediments of Tertiary e age. In the Tertiary f formation neither conformable nor unconformable lavas have been found, solely tuffitic sediments occur therein.

Microscopic examination of the pyroclastic rocks disclosed the presence of foraminifera in tuffs, tuff-breccias and tuffites from the Dent, Simporna and Sandakan peninsulas. These rocks consist of up to more than 90% of volcanic material which is partly reworked. The foraminiferal pyroclastic rocks made it possible to effect a direct determination of the age of the volcanic explosions. This matter of age is also of great importance for Tertiary stratigraphy, as these lithologically characteristic beds can serve as key horizons in future surveys.

Samples R. 74, R. 74a and L. 124 are particularly fossiliferous. Now and then the tuffite-breccias contain fragments of fossil-bearing limestone (R. 74a) and reworked fossil-remains of greater age (L. 124). I. M. van der Vlerk determined the presence of the following fauna:

R. 74 *and* 74*a*. Coarse foraminiferal sandy calcareous mixed crystal and lithic tuffite with 20% to 30% sedimentary material; lower course of S.Klumpang, Simporna Peninsula. R. 74: *Alveolinella bontangensis*, *Operculinella* sp., *Heterostegina* or *Cycloclypeus*, *Lepidocyclina* (small form), *Miogypsina* sp. Age: Tertiary f. R. 74a: *Carpenteria* sp., *Heterostegina* or *Cycloclypeus*, *Lepidocyclina* (small form), *Lepidocyclina* (*Eulepidina?*), *Miogypsina* (*Miogypsina* or *Miogypsinoides*). Age: *Tertiary* e_5-f_2, *probably* e_5.

J. 206. Coarse foraminiferal calcareous andesitic mixed vitric, lithic and crystal-tuffite with 40% admixed sedimentary material; head-waters of S.Subahan, E. of Darvel Bay. *Operculinella* sp., *Spiroclypeus* sp., *Lepidocyclina* sp. Age: *Tertiary* e_2-$_5$.

L. 124. Foraminiferal calcareous andesitic tuffite-breccia with vitrophyric lapilli and pyroxene crystals as main volcanic constituents and with 50% sedimentary material (see Plate II, Fig. 2); S.Segama, 8·3 km. WSW. of Kuala Mensuli. *Spiroclypeus* sp., *Operculinella* sp., reworked *Discocyclinae*. Age: *Tertiary* e_2-$_5$.

At some distance from the spot where sample L. 124 was taken, near the S.Mensuli, in a locality 700 m. NE. of Kuala Mensuli (S.Segama), there is a thick bed of tuff and volcanic breccia of which, unfortunately, no sample is available. Nevertheless this occurrence is worth mentioning, since according to P. Leicester's data the tuffs here normally cover a fossiliferous limestone which unconformably rests on the pre-Tertiary. This limestone (L. 109, L. 110) contains *Globigerina* sp. sp., *Lepidocyclina* (microspheric form) and *Nephrolepidina ferreroi Prov.*, and represents *Tertiary* e_5-*f*.

Wk. 104. Foraminiferal slightly calcareous andesitic tuffite-breccia, rich in vitric lapilli and with few sub-angular fragments of plagioclase and

augite; 15% sedimentary material (see Plate II, Fig. 1); middle course of S.Tungku, Dent Peninsula. This sample comes from the coarse andesitic agglomerates and conglomerates (Tungku-Tabanak layers), in which they form a concordant intercalation. According to W. Mohler's determination, this sample contains *Miogypsina*, cf. *Ubaghsi*, and belongs to *Tertiary e*. The age of the coarse pyroclastic Tungku layers can also be delimited indirectly. The Tungku layers from which sample Wk. 104 originates rest unconformably on pre-Tertiary and are steeply folded. Resting unconformably on them, and separated by a basal conglomerate, come the gently folded tuffitic-sandy-clayey to marly Sebahat layers, the basal beds of which contain, in the Tungku area, foraminifera fauna of Tertiary f age (samples Wk. 304, Wk. 314a and T. 4833). These data also indicate that sample Wk. 104 is evidently older than Tertiary f. This sample is furthermore of special value, since it cannot, petrographically, be distinguished from the other tuffites, which proves that the cement and the tuffitic intercalations in the thick series of volcanic agglomerates and conglomerates of the Tungku area are, both as to mineral composition and structure, analogous to the tuffites situated at greater distance from the explosion centres.*

Unfortunately the coarse foraminiferal calcareous dacitic tuffites with vitric and lithic material and crystal fragments (Rh. 53 and 54), found on the south-east coast of the Sandakan Peninsula between Tg. Prapat and the town of Sandakan, do not contain determinable foraminifera.

The palaeontological data referred to above show that the foraminiferal andesitic tuffite-breccias contain similar faunas. The genera *Operculinella*, *Spiroclypeus* and *Lepidocyclina* occur in three samples. Moreover, samples R. 74 and 74a contain *Alveolinella bontangensis* and *Miogypsina*. As a great many thin sections of these two rocks (some as large as 20 sq. cm.) have been examined, whereas one thin section only of each of the other samples was available, the results of the palaeontological examination do not absolutely prove that R. 74 and 74a are more recent. There is a possibility that if the other samples were examined in an equally thorough manner it would be found that they, too, contain *Alveolinella* and *Miogypsina*. This is likely to be the case with sample L. 124, since examples of reworked specimens of *Discocyclina* are often found in the *Miogypsina*-containing Tertiary e_5 in North Borneo. The age determinations of the four samples R. 74, R. 74a, J. 206 and L. 124 yield *Tertiary* e_5 in common and lie between the limit values *Tertiary* e_3 and *Tertiary* f_3. Sample Wk. 104 corresponds to *Tertiary e*; it is superimposed by layers of *Tertiary f* age. Another indirect determination is given by the above-mentioned Mensuli limestones of *Tertiary* e_5-*f* age, which are covered by tuffite beds. The age of the sedimentary pyroclastic series has thus been fairly exactly determined; the rocks are representative of the middle to upper parts of the *Tertiary e*, possibly also of the lower part of the *Tertiary f*, but certainly the *Tertiary* e_5. Some of the samples demonstrably lie upon the surface of unconformity between the *Tertiary* e_4 and e_5.

As the volcanic fraction of the pyroclastic rocks referred to above, unlike that of the more recent tuffitic sediments of the Sebahat layers, is for the greater part poorly rounded, it is also possible by means of these palaeontological determinations to make a fairly exact determination of the age of the highly explosive volcanic eruptions in North Borneo: blocks, lapilli and ashes were ejected during the upper *Tertiary e*, with certainty during the e_5 stage, and probably up to *Tertiary f*. It seems that at the time of the volcanic eruptions extensive areas were covered by a shallow sea, in which the showers of ejectamenta were deposited and mixed with sedimentary material.

Wanner (1921, op. cit. p. 185) concluded from the observations made by Stamm in the Segama area, that the volcanic eruptions had already begun at the time when the Tabanak beds which are identical with the volcanic agglomerates of the Tungku beds, the sample Wk. 104 of which

*The Tabanak beds of the Segama area and the Tungku beds found in the Dent Peninsula, the lithological composition of which is detailed in the stratigraphical correlation Table I (Chapter V), are definitely of the same age (Te in Tungku area). It is, however, not clear which stages of the *Tertiary e* they represent. It was postulated above that the unconformity observed in the Tungku area at the base of the andesitic agglomerate and conglomerate series corresponds to the bottom of the Te, and that the unconformity situated at the top of these coarse pyroclastic Tungku strata agrees with the boundary between Te_4 and Te_5. Further, it was assumed that in Segama area the Mensuli limestones and overlying tuff beds, both lying upon the surface of unconformity beneath Te_4/Te_5, are of a younger age than the Tabanak-Tungku beds, an inference not proven by field observation. It seems possible, also, that the coarse pyroclastic series of S.Tabanak-Segama and S.Tungku represent only the uppermost part of the Te, and overlie the important unconformity below Te_4/Te_5. In this case, the unconformity observed at the top of the Tungku layers would have to be placed between Te_5 and Tf. This discussion shows that even a minor shifting of the stratigraphical position of the coarse pyroclastic series would have considerable consequences. Future research will have to decide the answer to this problem.

represents *Tertiary e*, were deposited and continued till after the folding of these Neogene layers. This conclusion can be accepted for the other areas of the Dent and Simporna peninsulas: thus the Tertiary andesitic volcanism of North Borneo preceded, accompanied and survived the intensive orogeny in upper *Tertiary e*. Similar conditions, according to verbal data given by Dr. W. Mohler, seem to have prevailed in Netherlands East Borneo.

Now that it has been decided, on the grounds of petrographical and palaeontological arguments, that the Miocene tuffites and tuffite-breccias in the eastern part of North Borneo belong together and are of the same age, they may be considered as key horizons. In particular, the typical lapilli-rich tuffite-breccias should be made use of for the further division of the Tertiary areas. They may be of special interest for the division of series devoid of fossils, for, as is well known, tuffs and tuffites are in many countries considered excellent key horizons.

Petrology

1. Mineralogical Composition, Structure and Texture of the Dacite-Andesite-Basalt Series

The Tertiary volcanic rocks described in this chapter are light to dark grey, sometimes brown in colour, medium or fine-grained to glassy, and rarely vesicular. The types rich in glass are as a rule darker than those poor in it. Frequently it is possible to discern with the naked eye phenocrysts of feldspar, biotite, hornblende or pyroxene.

Microscopic examination disclosed the presence of leucratic to mesocratic rocks with a pilotaxitic, hyalopilitic to hyaline groundmass. Fluidal structure is rarely pronounced. Frequently, dependent on their size, the phenocrysts pass gradually into the groundmass microlites. When passing into holocrystalline hypabyssal rocks a microgranitic texture can be observed in acid varieties, a sub-doleritic texture in basic types (Krokström, 1932).

Among the phenocrysts, plagioclase nearly always predominates and forms clear, idiomorphic, zonal and amply twinned grains. It occupies on an average 30% to 60% of the entire volume (incl. groundmass). Alkali feldspar is missing. Several types contain quartz phenocrysts. The mafics present are: distinctly pleochroic (black-brown/straw-yellow to red-brown/light-yellow) biotite; olive-green, olive-brown to yellow-brown, sometimes also red-brown hornblende with strong absorption colour; slightly pleochroic (reddish/greenish) hypersthene; augite and very rarely olivine. It is a characteristic of the rock series examined that hornblende and biotite occur as frequently as augite, whereas hypersthene is mostly in small quantities and widely dispersed. As a matter of fact, this is also the case with other Tertiary and Quaternary volcanic rocks of the Malay Archipelago. Some optical data of the phenocrysts are shown in Fig. 8.

The groundmass contains, besides plagioclase, mainly pyroxene. Pigeonite-like clino-pyroxenes, with small optic axial angle, distinctly zonal structure and typical undulating extinction, are frequent as microlites. Several types are rich in haematite, particularly the andesites with red-brown phenocrysts of biotite and hornblende, which are difficult to distinguish from one another in many sections, and in magnetite or ilmenite. Quartz occurs in the groundmass of the dacitic samples, tridymite in that of the andesitic samples.

The typical reaction series of the mafics is discussed hereunder.

The rock suite to be dealt with is composed of biotite-hornblende- and pyroxene-dacites, of biotite-hornblende-, hornblende-hypersthene- and pyroxene-andesites, and of pyroxene-basalts. Basaltic types are rare in so far as the colour index is used as a criterion for drawing a line between andesite and basalt.

Fig. 8 gives information about the mineralogical composition of the principal rock types. Thirty effusive rocks, which were examined more closely according to the universal-stage method, have been divided into a dacite group and an andesite-basalt group, dependent on whether or not the varieties contain quartz as phenocrysts. Andesitoidal rocks with a glassy groundmass rich in silica, or with tridymite-containing, hemicrystalline groundmass have been classified as belonging to the andesite group. The two groups have been subdivided according to their predominant dark-coloured component; the pyroxene-bearing effusive rocks were arranged according to the partly measured, partly estimated, colour index. The specific gravity of the samples, which is also shown in Fig. 8, greatly depends on the glass content and the porosity.

As regards the anorthite determinations of the phenocryst feldspars on which this diagram has been based, it should be stated that the exact measurements according to the usual universal-stage method (diagrams of Reinhard, 1931, with corrections according to Spaenhauer, 1933) have been completed with determinations according to the zone method (Rittmann, 1929). Further, part of the determinations have been carried out by the immersion method, the results of which were reported on at an earlier date (Wenk, 1945). Of each thin section at least three grains have been thoroughly examined. The values shown on Fig. 8 can therefore be considered to cover the whole range of variation.

A striking feature is the almost constantly high anorthite content of the plagioclase phenocrysts, from the most acid dacites to the most basic quartz-free volcanics. Labradorite nearly always occurs. The span of varieties frequently extends from calcic andesine to bytownite. The presence of anorthite could be ascertained more rarely. The best developed zonal structures are shown by the plagioclases of the hornblende-andesites and the andesitoids respectively; their nuclei are for the greater part very calcic. In the case of sample Wk. 105, precision measurements of the splendidly clear and large crystals yielded 90% to 100% An for the cores and 45% for the outer zones. No so-called "high temperature optics" could be

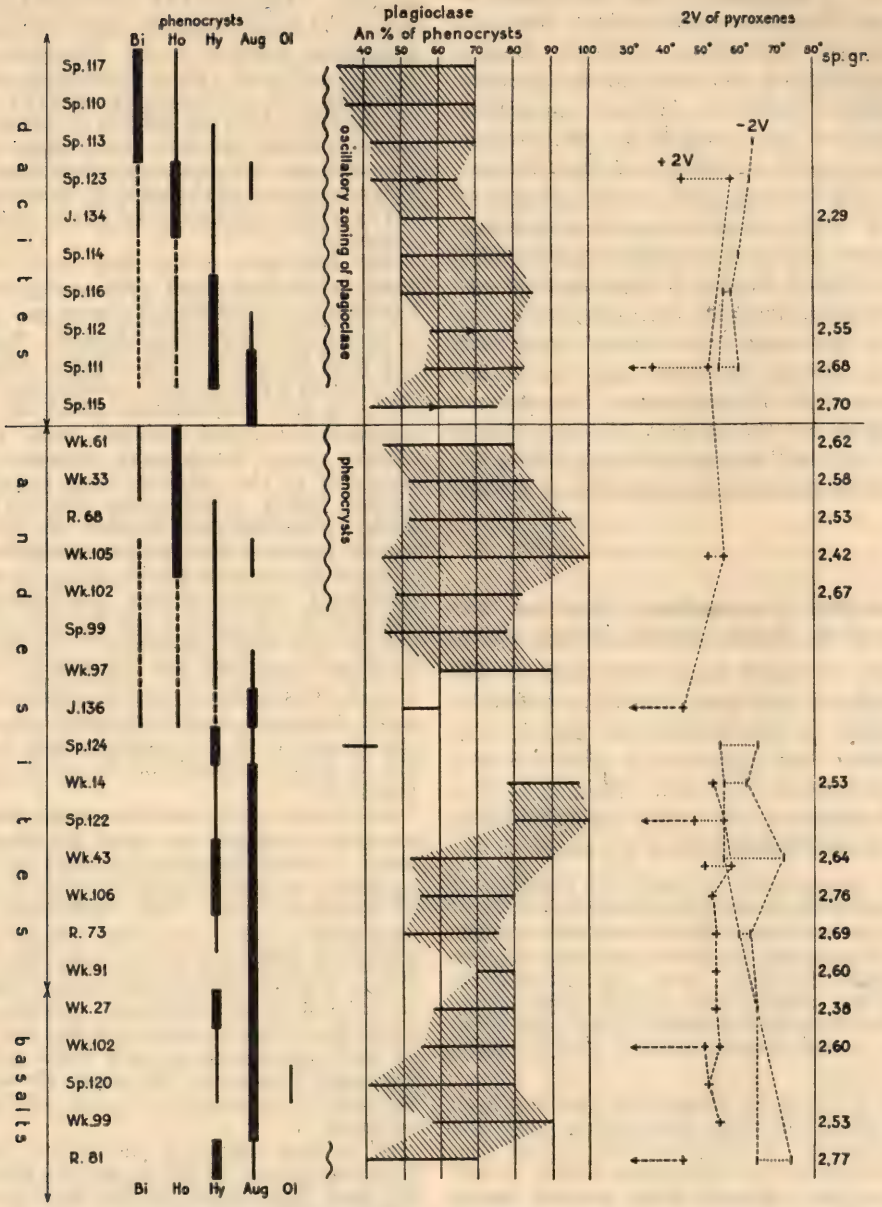


Fig. 8. Mineralogical composition and specific gravity of the Tertiary volcanic rocks

Optical properties and composition of the phenocrysts, as determined by universal stage methods. The samples are grouped in a dacitic series (with quartz phenocrysts) and an andesitic-basaltic series (without quartz phenocrysts, but partly with normative quartz, occult in the glassy matrix). In the row showing the distribution of the mafic phenocrysts, thick lines indicate chief constituents, thin lines accessory constituents and broken lines resorbed phenocrysts. Arrows indicate the sequence of zonal structures. Wavy lines show that such rocks contain plagioclase with oscillatory zoning.

ascertained here, nor in the case of some other examples. Determinations with reference to the tables of Köhler (1942) had the same result. Oscillatory microzonal structure has been established in nearly all the hornblende volcanics, but only exceptionally in the pyroxene-containing types. Where the phenocrysts gradually pass into the groundmass microlites, it was noted that the smaller but still measurable crystals are somewhat more sodic than the bigger ones. The microlites of the acid to intermediate volcanics which can no longer be measured on the universal-stage, but which can sometimes be determined according to the immersion method, are distinctly richer in albite than the phenocrysts. The microlites in the more rarely occurring rocks with reverse zonal phenocrysts, however, are richer in anorthite.

Notes on the Nomenclature

Fig. 8 shows convincingly that the anorthite-content of the plagioclase phenocrysts (cf. definitions of Rosenbusch, Johannsen, etc.) is no proper criterion for the mineralogical classification of the volcanic rock suite examined. For if one went only by this characteristic, most of the types examined would have to be classified as basalts or quartz-basalts, which would not be quite compatible with the colour index, nor with the mineralogical and chemical composition of the rocks. As a rule, however, the groundmass feldspars of the series are not determinable optically. So far, even X-ray methods have failed. Even if the microlites could be determined it would still be a difficult task to make an approximate calculation of the average anorthite content of the entire plagioclase. In the present report the colour index (ca. 40% mafic minerals) is used as the principal criterion for the division into andesites and basalts. Andesitoids (Niggli, 1931) or crypto-dacites (Ellis, 1948), i.e. rocks bearing SiO_2 in the glassy or hypocrystalline groundmass, are classified as belonging to the andesites. Leucocratic, calcic plagioclase-containing volcanic rocks without quartz phenocrysts, are classified as labradorite- or bytownite-andesites. If at some future time petrographers should come to an agreement as regards the designation for this disputed group, the rocks described could easily be renamed.

Description of 12 *important rock types* (chemical analyses of six of these rocks in Tables IV and V).

Sp. 110. *Hyalopilitic biotite-hornblende-dacite;* western head-waters of S.Tawau, Simporna Peninsula.

Light-grey rock with biotite, plagioclase and quartz phenocrysts of a size up to 5 mm., and hornblende prisms, up to 1 mm. long, in an orthorhombic pyroxene-bearing hyalopilitic groundmass. The rock is, megascopically, apparently weathered, but microscopically fresh.

Plagioclase has clear cores, showing oscillatory zoning, bordered by an apparently isotropic zone rich in dust-like inclusions, which in turn is surrounded by a clear outer shell. The anorthite content of the phenocrysts is from 70% to 35%; main oscillation between 60% and 40% anorthite; the average plagioclase is a calcic andesine. According to the immersion method the An-content is from 57% to 42%. The plagioclases of this rock have been thoroughly examined by Homma (1932, op. cit. Table II, Figs. 9–11, biotite-andesite). Quartz occurs in the form of bi-pyramidal, round-edged and irregularly corroded grains. The large biotite flakes are strongly pleochroic black-brown/straw-yellow; they have resorbed edges and are surrounded by a corona of yellow-brown hornblende, plagioclase, grey reflecting ore and orthorhombic pyroxene (see Plate III, Fig. 1). Yellow-brown hornblende forms small phenocrysts with absorption colours similar to those of the biotite; they gradually pass into the groundmass microlites. The hyalopilitic groundmass, besides glass, consists of plagioclase, hornblende, orthorhombic pyroxene, ore, occasionally biotite, also very small grains of a slightly double-refracting mineral with negative relief (? tridymite).

Mode:* plagioclase 30 vol.%, hornblende and biotite 11%, quartz 2%, groundmass 57%.

Sp. 123. *Hypersthene- and biotite-bearing hornblende-dacite with microgranitic matrix* = hornblende-quartz-diorite-porphyry; Tg. Sidongal, E. point of P. Timbun Mata.

From idiomorphic to round-edged phenocrysts, up to a size of 5 mm., of andesine and labradorite showing oscillatory zoning and inclusion zones. Universal-stage measurements of big crystals yielded from 42% (nucleus) to 64% An (marginal zone); measurements of microlites from 50% to 63% An. Rounded quartz phenocrysts. The prisms of green hornblende ($c \wedge n_\gamma$ 17°) up to 2 mm. size, are resorbed, partly converted into skeletons and, as a rule, surrounded by magnetite, clino-pyroxene ($+ 2V = 45°$ to 54°), hypersthene and plagioclase microgranules. Sometimes the hornblendes, while retaining their characteristic contours, are entirely replaced by microgranular aggregates of the above composition. Besides hornblende, biotite also occurs in skeletal form surrounded by ore, and, moreover, a few idiomorphic granules of slightly pleochroic hypersthene ($- 2V = 63°$). The phenocrysts gradually pass into the microgranitic, partly cryptocrystalline, groundmass containing interstitial glass.

The plagioclases of this rock (hornblende-"andesite") have been examined by Borloz (1924, op. cit. pp. 14–17) and by Homma (1932, op. cit. Tables I and II, Figs. 5–8). Their determinations accord well with one another and also with those of the present writer.

Wk. 61. *Hyalopilitic hornblende-biotite-labradorite-andesite:* boulder from volcanic agglomerate of S.Tungku, Dent Peninsula.

Grey rock, in which are discernible, with the naked eye, plagioclase and hornblende phenocrysts up to a size of 5 mm. The thin section has the characteristic feature that the mafics occur almost exclusively as phenocrysts, while the groundmass consists of at least 90% leucocratic components. The most frequent phenocryst is a distinctly coloured, black-brown/light-yellow idiomorphic hornblende with border of ore. In addition there are a black-brown/straw-yellow, distinctly optically biaxial biotite and a grey reflecting ore. The big, clear, idiomorphic plagioclase phenocrysts show oscillatory-normal zoning. Anorthite content

*Determinations of the modal composition (vol.%) refer to measurements with the aid of an integration table, if no other remarks (e.g. estimated) are given.

from 80% to 45%. The plagioclase phenocrysts gradually pass into the groundmass microlites. The groundmass, principally of plagioclase, also contains tridymite, light-brown glass and quartz in vesicles.

Mode: hornblende + biotite + ore 21 vol.%, plagioclase 17%, leucocratic groundmass 62%.

Wk. 33. *Hyalopilitic hornblende-bytownite/labradorite-andesite, biotite-bearing:* block from volcanic agglomerate of S.Mungkuou (Rashleigh), Tungku, Dent Peninsula.

Red-brown, compact, fresh effusive rock. Phenocrysts seldom reaching a size of 3 mm., mostly from 0·5 to 1 mm. For the greater part oscillatory microzonal plagioclase, amply twinned. Anorthite content: from 85% (nucleus) to 52% (boundary zone). Red-brown/greenish-yellow pleochroic and hardly distinguishable biotite and hornblende. Both mafics somewhat resorbed, rounded and bordered by a corona of haematite (Plate II, Fig. 4). Magnetite or ilmenite as inclusions in the hornblende and as separate granules, often bordered by haematite. Very fine-granular, plagioclase-rich, tridymite-bearing hyalopilitic groundmass. (See Tables IV and V.)

Mode: Plagioclase 22 vol.%, hornblende + biotite 16%, ore 4%, groundmass 58%.

Type of magma: quartz-dioritic.

R. 68. *Fluidal vitrophyric hornblende-bytownite/labradorite-andesite, hypersthene-bearing:* Pulau Klumpang, Simporna Peninsula.

Idiomorphic, clear phenocrysts, size up to 3 mm., of oscillatory zonal plagioclase with distinctly calcic, relatively uniform nucleus and glass inclusions. Anorthite content according to the universal-stage method: from 96% (nucleus) to 52% (outer shells); according to immersion method from 79% to 53% An. Idiomorphic phenocrysts, size up to 3 mm., of olive-green hornblende with many plagioclase inclusions. Unlike other hornblende-andesites, the hornblendes in this glassy effusive rock are rarely resorbed. Some granules of hypersthene, pleochroism greenish to reddish. Magnetite mainly in square-shaped granules. Ball-shaped aggregates of radially arranged, from brown to black, crystallites. Groundmass as a rule fluidal and glassy. (See Tables IV and V.)

Mode: plagioclase 32 vol.%, hornblende 10%, hypersthene 2%, ore 1%, groundmass 55%; colour index of the phenocrysts about 29%.

Type of magma: leuco-tonalitic.

Wk. 105. *Hyalopilitic hornblende-bytownite-andesite, augite- and hypersthene-bearing:* block from the volcanic conglomerates of S.Tungku, 1 km. above Kuala Pungulupi, Dent Peninsula.

Olive-brown, apparently weathered effusive rock with plagioclase phenocrysts as clear as glass, size up to 4 mm., and hornblende prisms, up to 6 mm. long. Section beautifully fresh. Idiomorphic, clear, twinned, anorthite-rich plagioclase. Nuclei of the plagioclases optically almost uniform and consisting of anorthite to bytownite (from 100% to 80% An). Narrow, normally zonal boundary zone with from 77% to 45% An. Predominant mafic is a distinctly pleochroic brown hornblende (dark brown/light yellow) with $c \wedge n_\gamma = 5°$. The big hornblende grains are resorbed and frequently show skeleton forms and reaction rims of ortho- and clino-pyroxenes, intermediate plagioclase and ore. The augite phenocrysts, size up to 1 mm., show optic axial angles of from + 52° to + 56°. There are, besides, slightly pleochroic hypersthene and grey reflecting ore. The phenocrysts gradually pass into the non-fluidal, hyalopilitic groundmass which contains a fair amount of brown glass. No micrometric analysis carried out in view of the coarse grain. However, the rock is distinctly leucocratic, since the plagioclase phenocrysts alone occupy more than 50% of the volume.

Sp. 124. *Amygdaloidal perlitic hypersthene-andesite, augite-bearing:* NE. of Mount Connor, in bay SSW. of Simporna.

White and grey speckled, vesicular effusive rock. Phenocrysts of clear, slightly zonal to fine-oscillating zonal andesine of a size up to 6 mm. (zonal structure mostly reverse; universal-stage measurements from 34% to 43% An; immersion method from 36% to 49% An), and of non-pleochroic, iron-rich hypersthene ($-2V$ nucleus 65°, outer zone 55°, corresponding to from 36% to 44% $FeSiO_3$), and little augite and ore in hyalopilitic, glass-rich and perlitic groundmass (Plate II, Fig. 3). Sharp separation between phenocrysts and groundmass. Vesicles filled with opal (isotropic, $n = 1{\cdot}496$), heulandite (biaxial +, $n_\gamma > 1{\cdot}522 < 1{\cdot}539$, $n_\alpha > 1{\cdot}496 < 1{\cdot}522$), chlorite and other undeterminable minerals.

Mode: plagioclase 21%, pyroxene + ore 3%, groundmass 76%.

Type of magma: problematic; abnormal for eruptive rocks (Tables IV and V); resembling granodioritic.

Wk. 14. *Hyalopilitic basalt or bytownite-andesite, augite- and hypersthene-bearing, rich in glass:* S. Mungkuou (Rashleigh), Dent Peninsula.

Glass-rich, grey-black, substantially plagioclase-bearing effusive rock. The phenocrysts consist principally of fresh, rounded, mostly twinned, normally zonal grains, up to a size of 3 mm., of from anorthite to bytownite with zonally enriched drop-shaped inclusions of brown glass. Anorthite content according to the universal-stage method from 97% (nucleus) to 78% (outer zone), according to immersion method from 90% to 76%. Few small phenocrysts of slightly pleochroic hypersthene ($-2V = 56°$ to 62°, corresponding to from 45% to 38% $FeSiO_3$) and of augite ($+2V = 53°$). A little grey reflecting ore. Fluidal, glassy groundmass with very fine plagioclase laths and ore granules. Sharp separation between phenocrysts and groundmass.

Wk. 43. *Hyalopilitic hypersthene- augite-bytownite/labradorite-andesite* = miharaite; boulder from volcanic agglomerate of S.Tungku, Dent Peninsula.

Grey, yellow-brown, somewhat weathered rock with phenocrysts, of a size of from 1 to 3 mm., predominantly of plagioclase, and of augite and hypersthene in equal quantities, as well as grey reflecting ore in hyalopilitic groundmass, consisting of intermediate plagioclase, pyroxene, ore and glass. Good separation between phenocrysts and groundmass. Anorthite content of

the clear, idiomorphic, substantially twinned and normally zonal plagioclases, often grown out into divergent glomeroporphyritic clusters, from 90% to 52%; — 2V hypersthene from 56° (nucleus) to 72° (boundary zone); + 2V augite from 52° to 58°, c ∧ n_γ 39°–41°.

Mode: plagioclase 39 vol.%, pyroxene 6%, ore 2%, groundmass 53%.

Sp. 122. *Hyalopilitic augite-hypersthene-bytownite-andesite* = miharaite; Bukit Sigalong, Simporna Peninsula.

Light-grey, fine-grained effusive rock. Sightly zonal granules, of a size up to 1 mm., of anorthite to bytownite are the principal phenocrysts. Anorthite content from 100% to 80%, high-temperature optic. Substantial quantity of augite (+ 2V = 56° to 48°) to pigeonite-like augite with optic axial angles about + 30° and distinctly undulating extinction; the latter occurring only as microgranules; also hypersthene. Very fine-grained, hyalopilitic groundmass. Sharp separation between phenocrysts and groundmass. (See Tables IV and V.)

Type of magma: belugitic.

Sp. 120. *Mesocratic, hyalopilitic olivine-augite-basalt, hypersthene-bearing:* western head-waters of S.Tawau, Simporna Peninsula.

Phenocrysts of reversely zoned plagioclase, size up to 1·5 mm., with andesine/labradorite nucleus and labradorite/bytownite outer zone. Anorthite content of the phenocrysts from 40% to 80% An; of the microlites from 49% to 75% An. Granules, size up to 1 mm., of olivine and augite (+ 2V of the latter 52°), some hypersthene and magnetite. According to their order of magnitude the phenocrysts pass into the hyalopilitic, but glass-poor and very fine-grained groundmass with microlites of pigeonite-augite. (See Tables IV and V.)

Type of magma: leuco-miharaitic.

R. 81. *Sub-doleritic hypersthene-basalt:* S.Klumpang, below the large southward bend of the river, Simporna Peninsula.

Fine-grained, dark-brown effusive rock. Normally zonal plagioclase with narrow sodic marginal zone; principally in the form of thin laths, from 0·1 mm. to 0·3 mm. long, rarely granules up to 0·5 mm. Anorthite content of the larger granules from 63% (nucleus) to 40% An (outer zone), of the fine borders (zone method) from 69% to 41% An. Hypersthene forms idiomorphic, somewhat resorbed crystals, size up to 1 mm., which are frequently surrounded by a corona of fine-grained augite (Plate III, Fig. 4). — 2V hypersthene from 74° (nucleus) to 65° (margin), corresponding to from 30% (nucleus) to about 36% $FeSiO_3$; no pleochroism. Pigeonite-like zonal augite with small optic axial angles (+ 2V of the nuclei 45°; outer shells with appreciably smaller axial angles) and distinctly undulating extinction, only in the form of microgranules. Interstices filled with aphanitic mesostasis. (See Tables IV and V.)

Mode: pyroxene 43 vol.%, plagioclase 38·5%, mesostasis 18·5%.

Type of magma: orbitic.

2. Mineralogical Description of Tuff-Tuffite Series

The preceding section considered both the lavas proper and the volcanic rocks contained in the pyroclastic deposits. The present section deals with tuff-breccias and tuffs, and with the tuffites belonging thereto. The tuffitic-sandy-clayey rocks which consist of more than 50% sedimentary material have been described together with the other Tertiary sediments (Chapter V).

As there appears to be no uniformity in the nomenclature of pyroclastic and sedimentary pyroclastic materials, it is desirable to review the definitions used in this paper. Most of the following are adopted from Wentworth and Williams (1932).

Tuff: Indurated pyroclastic rocks of grain generally finer than 4 mm. (volcanic ashes and dust). According to the predominance of glass, crystals of individual minerals or fragments of holocrystalline or partly glassy rocks, vitric tuffs, crystal-tuffs and lithic tuffs are distinguished. Tuffs may contain 0–10% sedimentary material.

Tuffite: Sedimentary tuff with 10% — 50% admixed sedimentary material. (Sediments with less than 50% volcanic material are termed tuffaceous clays, sands, etc.)

Tuff-breccia: Indurated pyroclastic rock composed of fragmental materials generally from 4 mm. to 3 cm. in diameter (mainly lapilli), while the matrix consists of the finer materials (4 mm. diam.) of the eruption.

Tuffite-breccia: Sedimentary tuff-breccia with 10% to 50% admixed sedimentary material.

Volcanic breccia: More or less indurated coarse pyroclastic rocks consisting chiefly of angular ejecta 32 mm. or more in diameter (volcanic bombs and blocks). They may be partly sedimentary or purely pyroclastic, contemporaneous or non-contemporaneous with the volcanic activity.

Volcanic agglomerate: Contemporaneous, coarse pyroclastic rocks containing a predominance of chiefly rounded or subangular fragments, greater than 32 mm. in diameter, lying in an ash or tuff matrix.

Volcanic conglomerate: Sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded and water-worn fragments.

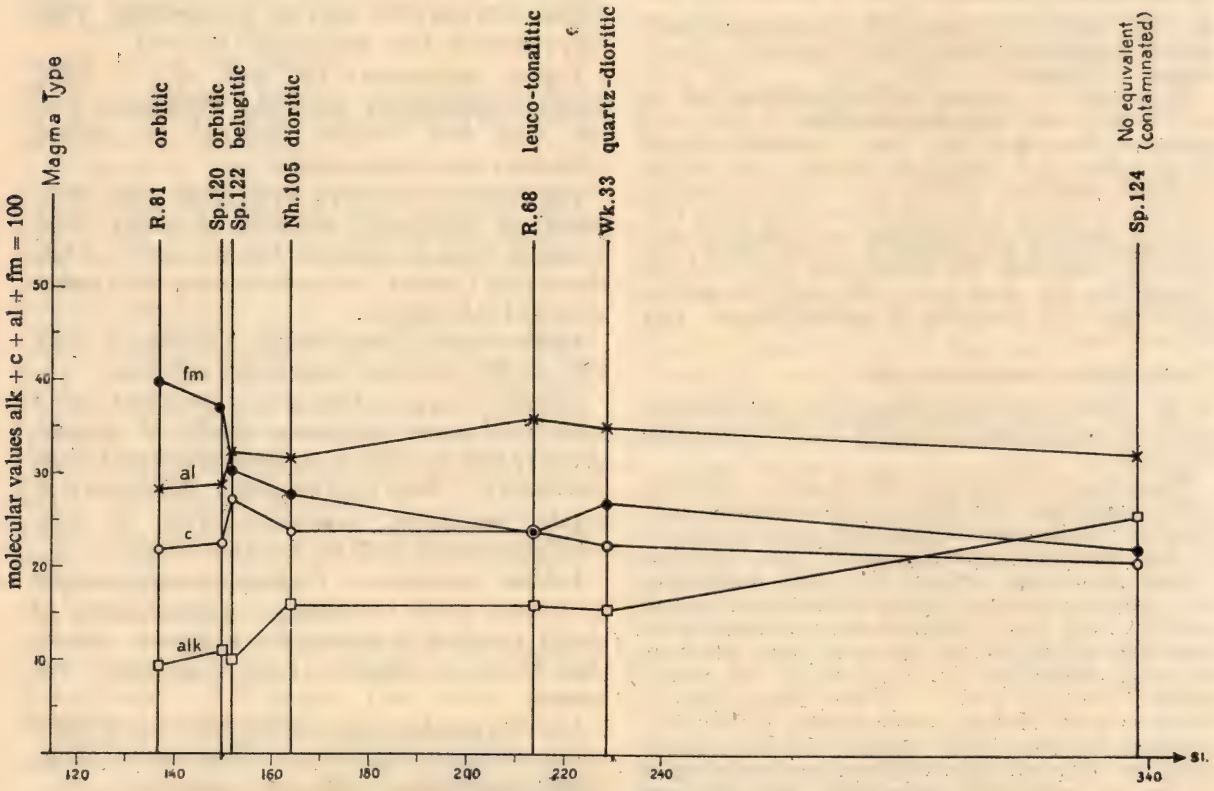
In the NE. and SE. parts of North Borneo occur from green-grey to brown-grey speckled tuffites and tuffite-breccias, which pass into real tuffs and tuff-breccias. The examined samples of these rock series originate from localities some of which are close together, others far apart, but all show a similar structure and composition as regards the range of

variations readily visible in a hand-specimen. The material in question is a mixed series of volcanic-sedimentary rocks of widespread distribution and of a really analogous composition. Some of the occurrences are associated with andesitic lavas, others are found in thick Tertiary sedimentary series and are the only proofs of volcanic activity at the time of deposition of that series.

The tuffites and tuffite-breccia, which exceed the tuffs and tuff-breccia in quantity, consist of lapilli, of sizes ranging from some millimetres to some centimetres, of biotite-hornblende-, hornblende- and pyroxene-dacite and andesite with from hyalopilitic to hyaline groundmass, of lapilli of glass, of angular fragments, more rarely of whole idiomorphic crystals of characteristic phenocrysts from the Tertiary volcanic series (from clear, oscillatory zoned andesine to labradorite, or bytownite; magmatically corroded quartz; hornblende and pyroxene) and of ash particles mixed with sedimentary material.

The angular crystal fragments and the well preserved magmatic resorption forms prove that the volcanic material had not been rolled and reworked to any appreciable extent after the showers of ash. The sedimentary cement of these mixed crystal and lithic tuffites is often calcareous-sandy and sandy, more rarely purely calcareous, or from marly to clayey; it contains quartz, carbonate, chlorite-serpentine, sometimes also varieties from glauconite to celadonite. The matrices of many tuffites have foraminifera embedded therein. The faunas in these tuffites and the determinations of the age of the volcanism based on them are dealt with on p. 33.

A striking feature disclosed in the microscopic examination is that the light- and dark-coloured constituents of the dacites and andesites are invariably beautifully fresh, and this is also the case with the pure tuffs (Tungku area). As regards the tuffites, however, only the plagioclases and the quartz are clear and do not show any alteration, while the mafics have almost invariably been altered into chlorite-serpentine. During the sedimentary processes following their deposition, the pyroxenes and amphiboles apparently were transformed rapidly into the hydrated and silica-poor



$$si = \frac{\text{molecular value } SiO_2}{\text{molecular values } Al_2O_3 + FeO + MgO + CaO + Na_2O + K_2O} \times 100$$

where the molecular value is $\frac{\text{weight \%}}{\text{molec. weight}} \times 1000$

Fig. 9. Variation diagram of the Tertiary volcanic rocks
Niggli molecular values.

serpentine and chlorite minerals; the intermediate to calcic plagioclases, however, have not been altered during this process. The preservation of the plagioclases must not, therefore, be considered as a general criterion for drawing conclusions as to the presence or absence of submarine weathering.

According to the data given on pp. 33 and 34, andesitic to dacitic tuffs, tuffites and tuffite-breccia occur in the S.Klumpang and the S.Subahan of the Simporna Peninsula, in the S.Segama and the S.Tungku of the Dent Peninsula, and also in the Sandakan Peninsula (P. Berhala and in the vicinity of Sandakan). These rocks are hardly distinguishable from one another either megascopically or microscopically and must be considered as belonging together and as being of the same age. The samples found in the Sandakan area are particularly rich in ash and in magmatically corroded quartz crystals. According to the reports and maps by various geologists and as a result of the microscopic examination of rock samples, further occurrences are reported in the following localities: S.Tabanak, S.Pakat, S.Silibukan, S.Mungkuou and S.Tabin in the Dent Peninsula and S.Gumgum on the Sandakan Peninsula. These samples together form a petrographic unit.

In conclusion, it may be observed that field geologists have mistaken some isolated occurrences of Tertiary dacitic to andesitic tuff-breccia for pre-Tertiary rocks of the type of the Pulau Melayu breccia (Danau Formation). It is easy to show that the field diagnosis is wrong. Certainty on this point can be obtained, by microscopic examination, from the hyalopilitic to hyaline andesite inclusions; from the crystal fragments of clear, oscillating zonal, intermediate to calcic plagioclase; and from the magmatically corroded quartz and fresh crystals of hornblende, biotite and pyroxene, characteristic of the Tertiary volcanic rocks. The volcanic breccias of the Danau Formation bear sodic and often highly decomposed plagioclases and do not contain fresh glass. Moreover, they are as a rule associated with other characteristic rocks (cherts and ophiolites), so that the age of the rock can generally be determined in the field.

3. Chemical composition

The results of six chemical analyses of volcanic rocks from the E. coast carried out by P. Bearth and W. Vögtli, and the molecular values calculated on the basis thereof, are shown in Tables IV and V on pp. 44 and 45. Unfortunately, the analyses refer only to varieties without quartz phenocrysts, as insufficient fresh material was available from the dacitic types.

The following data show that the Borneo rocks are similar to known magma types of the calc-alkali series. Rocks of analogous composition are of widespread occurrence among the Tertiary and Quaternary volcanic series of the entire Malayan Archipelago.

	si	al	fm	c	alk	k	mg
Wk. 33 hornblende-biotite-labradorite-andesite	229	35	27	22·5	15·5	·31	·36
Quartz-dioritic magma-type	225	32	31	19	18	·25	·45
Augite-hypersthene-hornblende-andesite, Java, Willems No. 822	188	34	28·5	22·5	15	·23	·40
R. 68 vitrophyric hornblende-bytownite-andesite	214	36	24	24	16	·42	·45
Leuco-tonalitic magma-type	220	39	24	21	16	·50	·30
Andesite, Aroroy, Masbate, Ph. Ilds, A. Cox, 1908	182	33	25	25	16·5	·26	·49
Sp. 120 olivine-basalt	150	29	37·5	22·5	11	·24	·48
Orbitic magma-type	135	27	42	21·5	9·5	·25	·50
Basalt, Tidore, Willems No. 781	168	27·5	38·5	22	12	·26	·57
Pyroxene-andesite, Gg. Aron, Sangi, Roothaan (Zürich) unpublished	147	27	37	25·5	10·5	·32	·35
Sp. 122 hypersthene-augite-bytownite-andesite = miharaite	152	32·5	30·5	27	10	·25	·55
Belugitic magma-type	130	29	32	29	10	·15	·50
Andesite, Mayon, Ph. Ilds, Iddings, 1910 ..	140	31	32·5	26·5	10	·16	·44
R. 81 hypersthene-basalt	137	28·5	40	22	9·5	·12	·55
Orbitic magma-type	135	27	42	21·5	9·5	·25	·50
Basaltic lava, Krakatau, Willems No. 615 ..	143	28	39	23	10	·29	·45
Basalt, Mt. Penanggungan, Java, Willems No. 560	139	28	38	24·5	9·5	·30	·50

N.B. Willems Nos. refer to H. W. V. Willems: On the magmatic provinces in the Netherlands East Indies, Verh. Geol. Mijnbouwk.-Genootschap v. Nederl. en Kol. Geol. Ser. Part XII, 1940.

The Niggli values of the volcanics (also of the hornblende-andesite from Tg. Sirar, W. coast) are shown in the variation diagram of Fig. 9. One of the most striking features of this diagram is the uniformly high values of c and al over a wide si range, and indeed the flatness of the curves. The difference al–alk is also, except in the case of an abnormal rock Sp. 124 (si 338), invariably great (about 20), which leads to the conclusion that the anorthite component essentially contributed to the building up of the feldspars of both the normatively quartz-free and the quartz-bearing rocks. Consequently the rocks are of Pacific type.

The only sample which shows a chemical composition abnormal for magmatic rocks is the perlitic hypersthene-andesite, Sp. 124, pp. 44 and 45. Its molecular values are comparable with types varying from granodioritic to adamellitic, but its al value is lower and its c value much higher. It might also be compared with the leuco-sommaitic magma type, but with a much higher si and a somewhat lower k. The lava corresponding to sample Sp. 124 was evidently contaminated by sedimentary material.

The good petrochemical agreement between the Miocene volcanics of North Borneo and the Miocene to Recent Pacific volcanics from other parts of the archipelago, shows that there is a general characteristic differentiation tendency for the entire neo-volcanic region. It is possible that the striking flatness of the curves in the variation diagram (Fig. 9), which shows a great variability of si with much smaller deviations in al, fm, c and alk, is connected with a certain assimilation of the predominantly sandy Tertiary layers by the magmas.

The basic members of the North Borneo volcanics (R. 81, Sp. 120, Sp. 122) appear on the si-alk diagram under Niggli's main group of the basalts (plagioclase-basalts) (see Burri-Niggli, 1945). In this diagram they are clearly distinguishable from the ophiolitic rocks, which with the same si range can be seen in the diagram (Fig. 22) to fall within the field of alkali-basalts.

The petrochemical differences and analogies between Simporna volcanics, Kinabalu intrusive rocks and Danau ophiolites are discussed on p. 63.

4. Petrological Problems

Reaction Series of Mafic Minerals

In some varieties of the series of volcanic rocks examined, the four important dark-coloured constituents—biotite, hornblende, hypersthene and ordinary augite—occur simultaneously. A fifth mafic constituent, namely, pigeonite-augite has been found in several samples (see fig. 8). These five dark-coloured constituents, however, are never all in equilibrium with one another, which is proven by their reaction rims and their uneven distribution as regards phenocrysts and groundmass microlites.

Biotite occurs in many dacitic and andesitic rocks as phenocryst, and also, but only exceptionally, as a groundmass microlite. Hornblende frequently forms phenocrysts, but more rarely the mineral is found in the groundmass. The groundmasses of some biotite-hornblende volcanics contain hornblende, but no biotite. These two mafics, which contain water and aluminosilicate components, mostly occur only as phenocrysts, while pyroxenes occur in the groundmass.

Of the two types of pyroxene the ortho-pyroxenes occur more frequently in the phenocryst stage, though quantitatively they are not of greater importance than the clino-pyroxenes. Hypersthene and ordinary augite occur both as phenocrysts and as microlites, though here, too, certain variations in the behaviour of the two pyroxenes can be observed. In various samples hypersthene has formed big crystals; augite, however, occurs only as small granules and forms part of the groundmass. The pigeonite-augites and pigeonites, characterized by small optical axial angles (+ 2V 45° in the nucleus, but considerably smaller in the outer zone), distinctly zonal structure and a typical undulating extinction, could be observed almost exclusively in the form of microlites and small phenocrysts, but exceptionally also as outer zones of the augite phenocrysts. The following sequence of crystallization can be reconstructed with reference to the observations made in the various rocks: biotite → hornblende → hypersthene → ordinary augite → pigeonite-augite.

The same sequence is arrived at when analysing the resorption processes, the reaction rims and the inclusion conditions. The following examples taken from an ample amount of data give a rough impression of the subject:

Sp. 110: Biotite, resorbed and with reaction rim of hornblende, hypersthene, plagioclase and ore (Plate III, Fig. 1).

Sp. 123 *and Wk.* 105: Hornblende, resorbed and with reaction rim of ortho- and clino-pyroxenes, plagioclase and ore.

J. 136: Hypersthene phenocrysts, resorbed; hypersthene skeletons bordered by ordinary augite (single crystal); hornblende phenocrysts, resorbed and with rim of ore or a corona of clino-pyroxene; biotite almost entirely resorbed and replaced by ore dust. Pigeonite-augite in groundmass.

Sp. 111: Iron-rich hypersthene phenocrysts, resorbed and bordered by pigeonite-augite; clino-pyroxene granules with ordinary augite in the nucleus, passing into pigeonite-augite zone (+ 2V from 47° to 37°; extreme outer zone with still smaller, unmeasurable axial angles). Relics of hornblende and biotite.

R. 81: Mg-rich hypersthene, somewhat resorbed and bordered by microgranules of distinctly zonal pigeonite-augite-like clino-pyroxenes (Plate III, Fig. 4).

The reaction series biotite → hornblende → Mg → Fe-rich hypersthene → ordinary augite → pigeonite-augite, and mainly the general sequence biotite + hornblende → hypersthene + ordinary augite → pigeonite augite, is proven by many further examples. They show that at first big biotite and hornblende crystals were formed, which were originally in equilibrium with the melt, for when the lava is rapidly cooled and the groundmass is glassy these phenocrysts do not show any resorption. When cooled more slowly the phenocrysts of biotite and hornblende were mostly corroded, bordered by microgranules of ore, pyroxene and plagioclase, or resorbed to relics; in the course of the solidification of the magmatic melt they became

unstable. It is possible that originally some andesites, in which now only pyroxenes can be observed, contained hornblende, or biotite and hornblende, but that these components were afterwards entirely resorbed.

In this connection it may be added that the Mg, Fe and Ca calculated as forming silicate compounds (see Table V) occur in the analysed volcanic rocks of North Borneo in such proportions as to allow the presence of the combinations biotite-hornblende or hypersthene-augite. Rocks rich in $CaSiO_3$ and having γ values $> 0{\cdot}20$, which postulate the presence of augite or diopside, are not present. A diagram summarizing the results showed that such $CaSiO_3$-rich rocks which fall between the hornblende and augite-diopside fields, rarely occur among the Tertiary and Quaternary volcanics of the Malay Archipelago. It might be expected, therefore, that hornblende, either alone or combined with biotite or hypersthene, would occur in all six analysed samples of Borneo rocks; but it is present in only two samples. The quantity and mode of combination of Ca, Na and K in aluminosilicate compounds have in no way hampered the forming of hornblende, as they did that of biotite in some rocks with low k-values; in these cases one would expect to find the combination of hornblende with hypersthene. The main hindrance to the crystallization of hornblende appears to have been the lack of water, fluorine, etc. The question referred to above can thus be answered by stating that possibly hornblende had formed in all six analysed samples during the earlier crystallization processes but that it was afterwards entirely resorbed. Hornblende is by far the predominant mafic in the Indonesian Tertiary plutonic to sub-volcanic rocks of similar chemical composition.

The reaction sequence found for the volcanics of the E. coast of North Borneo, viz. biotite → hornblende → ortho-pyroxene → clino-pyroxene, shows an inverse order as compared with that found in intrusive rocks, viz. pyroxene → hornblende → biotite, which is the Bowen sequence, recognized to be the normal one. The abnormal reaction series of the Borneo volcanics is assumed to be due to the magma progressively losing its volatile components, including water-vapour. The big phenocrysts of biotite and hornblende which had formed at great depth became unstable when the magma and the crystallized phases in suspension therein arose during extrusion, and when volatile components constantly escaped through open volcanic vents they reacted with the materially changing melt. Only with rapid rise and rapid outflow of the lavas could the biotite and hornblende crystals be preserved in the glassy solidifying melt. Otherwise, biotite and hornblende reacted with the melt now poorer in mineralizing agents. The unstable phenocrysts were partly or entirely resorbed and water-free mafics were formed instead. It is possible that these processes took place intermittently, so that during periods when the volcanic vents were closed, biotite and hornblende could crystallize again as a result of the accumulation of volatile components in the upper magmatic layers.

As soon as the formation of biotite and hornblende ceases owing to the magma becoming poor in water, or to resorption of these crystals, more feldspar forms, since alkalis and calcium in aluminosilicate compounds can only then pass into feldspar. These phenomena also affect the zonal structure of the plagioclase phenocrysts and the anorthite content of the microlites. Since, according to observations made by Wenk (1945), the aluminosilicate components of the hornblendes have an anorthite content which approximates to that of the associated calcic plagioclase nuclei, the resorption of hornblende may cause reverse zonal structure of the plagioclase phenocrysts and favour the formation of calcic plagioclase microlites. Such conditions could actually be observed in some pyroxene volcanics (Sp. 112, 123) containing resorbed hornblende.

The reaction series of the pyroxenes is normal; it leads from Mg-rich to Fe-rich hypersthene and from augite (exceptionally from diopside) to clino-pyroxenes poor in Ca and rich in Fe.

It may be concluded from the existing scanty but exact descriptions of other Indonesian effusive rocks that the resorption of hornblende and the formation of pyroxene very frequently occur in the groundmass stage.

The hornblende → pyroxene reaction has frequently been similarly interpreted by other petrologists, notably by Larsen and Irving (1937) with reference to the Tertiary volcanic rocks of the San Juan region in Colorado.

As regards North Borneo and the Malay Archipelago as a whole, the above interpretation is quite in line with the highly explosive character of the Pacific, Neogene to Quaternary vulcanism.

Anorthite content of Plagioclase Series

Characteristic features of the Tertiary volcanic rocks of North Borneo are the high normative anorthite content and the usually still higher modal anorthite content of their plagioclase phenocrysts. Various volcanic rocks, which are supersaturated with silica and distinctly leucocratic, carry phenocrysts with large uniform bytownite nuclei and narrow marginal zones of labradorite and calcic andesine.

The high normative anorthite content is due to the high Ca and Al and to the relatively low alkali values. This high anorthite content is maintained through a wide range of silica values. The fact that the normative $\frac{An}{Ab+An}$ ratio of the intermediate types R. 81, Sp. 120 and Sp. 122 exceeds 0·5 is not surprising, since many such effusive rocks are known from the circum-Pacific region (miharaite, bandaite, sakalawite, etc.). A surprising fact, however, is the ratio, which varies around 0·5 in the andesitic rocks R. 68 and Wk. 33, which are leucocratic and rich in silica, but do not contain quartz phenocrysts. As far as can be concluded from the modal anorthite content, it is likely that the genuine dacites also show an exceptionally high normative anorthite content and thus represent extremely Pacific types. In Fig. 19 the silica saturation coefficient α has been placed opposite the $\frac{An}{Ab+An}$ ratio. This diagram, which does not include the rocks undersaturated in silica, clearly shows the special position and the distinctly Pacific character of the Miocene volcanic rocks as compared with the other eruptive rocks of North Borneo.

TABLE IV. CHEMICAL ANALYSES OF TERTIARY IGNEOUS ROCKS AND ROCK-FORMING MINERALS

	Nh. 411	H.	A.	Wk. 66	Wk. 65	Nh. 473	Nh. 417	Nh. 422	Nh. 424	Nh. 105	R. 81	Sp. 122	Sp. 120	R. 68	Wk. 33	Sp. 124
SiO_2	62·79	42·69		59·39	52·83	59·75	60·33	58·76	69·05	55·44	53·65	53·79	54·51	60·96	62·82	67·47
TiO_2	0·57	1·53	none	0·60	0·65	0·95	0·96	0·95	0·40	0·83	0·50	2·30	1·47	0·11	0·75	1·41
Al_2O_3	15·55	10·88	19·47	14·19	10·33	15·56	13·75	15·48	15·16	18·45	18·90	19·59	17·93	17·45	16·16	10·91
Fe_2O_3	1·16	3·95	none	3·28	2·31	2·77	4·04	1·28	0·82	4·69	1·95	2·76	2·21	3·19	5·89	1·89
FeO	3·80	14·15		4·68	9·15	3·51	4·20	4·88	1·48	2·70	6·55	3·17	6·30	1·51	0·19	0·79
MnO	0·10	0·32		0·11	0·28	0·06	0·10	0·12	0·01	0·06	0·07	0·21	0·14	0·06	0·07	0·03
MgO	2·55	9·67	none	3·66	8·62	3·47	3·63	4·51	0·84	2·35	5·85	4·05	4·35	2·06	1·82	1·52
CaO	4·73	12·19	none	5·85	10·70	6·17	5·18	5·11	3·31	7·56	8·04	8·86	7·72	6·40	5·75	3·80
Na_2O	3·37	1·82	3·27	3·70	2·76	2·72	2·58	2·34	3·02	3·68	3·40	2·70	3·18	2·74	3·12	3·16
K_2O	4·82	1·21	12·30	3·18	0·82	2·56	3·78	3·75	2·79	2·76	0·72	1·36	1·48	3·03	2·06	3·24
H_2O^+	0·43	1·71		1·02	1·17	1·58	1·52	1·53	1·85	0·83	0·29	0·85	0·41	1·60	0·27	3·00
H_2O^-	none	0·10		0·10	0·10	0·80	0·25	1·06	0·25	0·45	0·18	0·20	0·13	0·60	0·49	1·00
P_2O_5	0·24			0·35	0·19	0·21	0·20	0·16	0·18	0·26	0·22	0·14	0·48	0·18	0·34	2·02
CO_2									1·02							
F					0·30											
V_2O_3		0·19														
Cr_2O_3					0·06											
	100·11	100·41		100·11	100·27	100·11	100·52	99·93	100·18	100·06	100·38	99·98	100·31	99·89	99·73	100·24
−O for F					0·08											
					100·19											
Sp. gr.	2·73	3·26		2·73	2·93	2·64	2·64	2·68	2·60	2·50	2·77	2·78		2·53	2·58	2·34

TABLE V. MOLECULAR BASE AND NIGGLI VALUES OF TERTIARY IGNEOUS ROCKS

No.	Q	L	M	Sp	Ru	Cp	π	k	γ	mg	α	si	al	fm	c	alk	ti	Magma type	Rock name
																			Kinabalu intrusion
Nh. 411	42·0	43·4	13·8	—	0·4	0·4	·18	·49	·20	·48	2·84	220	32	28	18	22	1·5	opdalitic/si-monzonitic	hornblende-quartz-monzonite
Wk. 66	38·2	39·5	21·2	—	0·4	0·7	·20	·36	·21	·46	1·68	185	26	37	19·5	17·5	1·4	monzonite-dioritic	hornblende-granodiorite
Wk. 65	29·3	26·3	43·5	—	0·5	0·4	·31	·17	·27	·57	0·81	122	14	52	26·5	7·5	1·1	alk-issitic	hornblende-rich inclusion in Wk. 66
Nh. 473	43·5	38·5	16·9	—	0·7	0·4	·36	·38	·12	·50	3·17	197	30	34	22	14	2·4	tonalitic	hornblende-biotite-quartz-gabbro-diorite-porphyry
Nh. 417	41·4	37·1	20·4	—	0·7	0·4	·24	·49	·15	·45	2·45	196	26·5	39·5	18	16	2·4	monzonite-dioritic	hornblende-biotite-micro-granodiorite
Nh. 422	41·2	39·5	18·3	—	0·7	0·3	·32	·51	·07	·57	2·44	188	29·5	38	17·5	15	1·0	monzonite-dioritic	biotite-hornblende-granodiorite porphyry
Nh. 424	56·7	36·9	3·3	2·5	0·3	0·3	·26	·38	·00	·40	29·2	340	44	15·5	17·5	23	1·6	granodioritic	biotite-rhyodacite
Nh. 105	36·6	45·8	16·4	—	0·6	0·6	·34	·33	·20	·37	1·11	164	32	28	24	16	1·9	dioritic	hornblende-labradorite-andesite
																			East coast volcanics
R. 81	34·9	41·4	22·9	—	0·3	0·5	·49	·12	·05	·55	0·96	137	28·5	40	22	9·5	1·0	orbitic	hypersthene-basalt
Sp. 122	38·4	42·4	17·3	—	1·6	0·3	·54	·25	·12	·55	1·76	152	32·5	30·5	27	10	4·9	belugitic	hypersthene-augite-bytownite-andesite
Sp. 120	36·5	40·8	20·7	—	1·1	0·9	·44	·24	·08	·48	1·34	150	29	37·5	22·5	11	3·1	orbitic	olivine-basalt
R. 68	45·9	42·6	11·0	—	0·1	0·4	·38	·42	·12	·45	4·56	214	36	24	24	16	0·2	leucotonalitic	vitrophyric-hornblende-bytownite-andesite
Wk. 33	47·9	39·6	11·3	—	0·6	0·6	·38	·31	·07	·36	5·70	229	35	27	22·5	15·5	2·2	quartzdioritic	hornblende-biotite-labradorite-andesite
Sp. 124	54·0	33·9	6·9	—	1·1	4·1	·11	·40	·05	·52	13·7	338	32	22	20·5	25·5	5·3		amygdaloidal hypersthene-andesite

The relationship between normative and modal anorthite content is best expressed by Fig. 10. This diagram also shows that the plagioclase phenocrysts are richer in anorthite than would be expected on the ground of the chemical composition of the rock. Since no other mineral phases containing Na aluminosilicate occur, much albite must be contained in the glassy groundmass and in the plagioclase microlites, as is mostly the case with insufficient reaction between crystal and residual melt in volcanic rocks. The same figure also shows the curve resulting from Bowen's equilibrium diagram of the plagioclases, which indicates the composition of the first, most calcic plagioclases which are in equilibrium with certain melts in the simple Ab-An system. It has been found that the nuclei of the plagioclases examined are more calcic

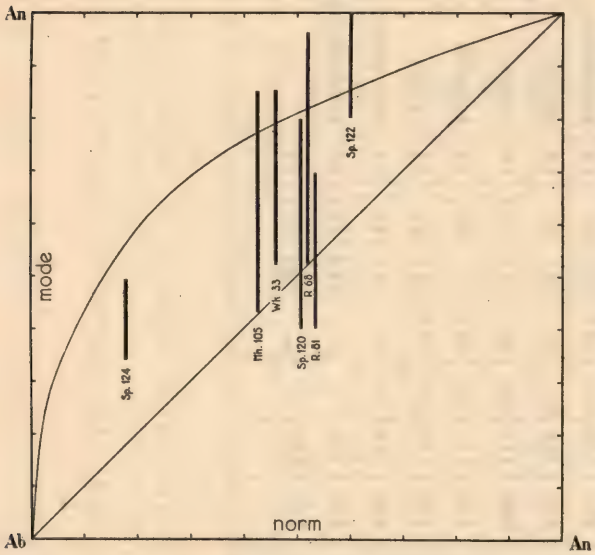


Fig. 10. Relation between normative and modal anorthite content in the volcanic rocks from the E. coast of North Borneo

The curved line indicates the composition of the first formed crystals in equilibrium with melts of given composition (according to the equilibrium diagram of the system anorthite-albite, established by Bowen).

than the initial crystals which, according to experimental observations, occur in the simple Ab-An system in melts of equal anorthite content. These relations have been discussed elsewhere with reference to additional data (Wenk, 1948). It seems that the curve representing the initial crystals of plagioclase in complex systems has shifted a little, and that unequal migrations of crystal and melt played an important part in the formation of the volcanic rocks described.

The almost uniformly high anorthite content of the plagioclase phenocrysts occurring in both the most acid dacites and the most basic quartz-free volcanic rocks, might be due partly to such migrations and partly to the fact that in the viscous acid magmas the reaction between crystal and melt was seriously impeded. This latter phenomenon may be illustrated by the following comparison. The most basic effusive rock analysed, the sub-doleritic hypersthene-basalt (R. 81) with a normative anorthite content of 53% and a specific gravity higher than that of any other analysed sample, namely, 2·77, contains only one generation of plagioclases, with from 69% to 40% anorthite. These plagioclases are as calcic as the phenocrysts of the leucocratic hyalopilitic biotite-dacite (Sp. 113) (Fig. 8). In this acid rock the reaction of melt and crystals was much less marked than in R 81; it is likely that the initial crystals rich in anorthite were preserved, and that the microlites are therefore rich in albite.

In view of these phenomena, therefore, the division of the basalts and andesites according to the nature of their plagioclase phenocrysts is very problematic, for the anorthite content of the plagioclase phenocrysts depends not only on the chemical composition of the melt but also on the solidification process, the kind of reaction between crystal and melt, the question as to whether or not Na-Ca-aluminosilicate components are also contained in other mineral phases, etc. Thus, for instance, experience has shown that a melt with an Ab-An ratio of about 60 : 40, when rapidly solidified, and when there is insufficient reaction between crystal and melt, causes phenocrysts with from 90% to 50% anorthite to form in a glassy groundmass; with slower solidification and a much better reaction, phenocrysts with an anorthite content of from 55% to 30% are formed. In the latter case the rock in question is an andesite; the first-mentioned rock, however, would have to be considered as a basalt when adopting the anorthite content of the plagioclase phenocrysts as a criterion, but this does not, in our opinion, offer a satisfactory solution.

List of Tertiary igneous rocks included in Tables IV and V.

Igneous rocks of Mount Kinabalu region, West Coast

Nh. 411: Hornblende-quartz-monzonite (monzonite-granite), coarse-grained. Boulder derived from the south flank of Mt. Kinabalu, S.Liwagu, WNW. of Ranau. Analysis by J. von Steiger.

H.: Green hornblende of sample Nh. 411. Analysis by J. von Steiger.

A.: Potash-soda feldspar of sample Nh. 411. Analysis by J. von Steiger.

Wk. 66: Hornblende-granodiorite, medium-grained. Low's Peak, summit of Mt. Kinabalu. Analysis by J. von Steiger.

Wk. 65: Hornblende-rich quartz-dioritic inclusion in hornblende-granodiorite. Summit plateau of Mt. Kinabalu. Analysis by J. von Steiger.

Nh. 473: Hornblende - biotite - quartz - micro - gabbro - diorite, hypersthene-bearing = micro-tonalite. SW. of Paranchangan, E. of Mt. Kinabalu. Analysis by P. Bearth.

Nh. 417: Hornblende-biotite-microgranodiorite, porphyritic. Summit of Bukit Kargan, SE. of Paranchangan. Analysis by P. Bearth.

Nh. 422: Biotite - hornblende - micro - granodiorite, augite-bearing and hypersthene-bearing. S. Merali, below Kg. Tadul, head-waters of S.Sugut. Analysis by P. Bearth.

Nh. 424: Biotite-rhyodacite. S.Merali, below Kuala Bawain. Analysis by P. Bearth.

Nh. 105: Hornblende - labradorite - andesite, augite - bearing. W. part of Tg. Sirar, N. part of west coast. Analysis by P. Bearth.

Volcanic rocks from Simporna and Dent Peninsulas, East Coast

R. 81: Hypersthene-basalt, sub-doleritic, with microlites of pigeonite-augite. Middle course of S.Klumpang, Simporna Peninsula. Analysis by P. Bearth.

Sp. 122: Hypersthene - augite - bytownite - andesite, hyalopilitic, with microlites of pigeonite-augite = miharait. Bukit Sigalong, Simporna Peninsula. Analysis by P. Bearth.

Sp. 120: Olivine-basalt, hypersthene-bearing, hyalopilitic, with microlites of pigeonite-augite. Western head-waters of S.Tawau, Simporna Peninsula. Analysis by P. Bearth.

R. 68: Vitrophyric hornblende-bytownite-andesite, hypersthene-bearing, fluidal. Pulau Klumpang, Simporna Peninsula. Analysis by P. Bearth.

Wk 33: Hornblende - biotite - labradorite - andesite, hyalopilitic. S.Mungkuou (Rashleigh), W. of Tungku, Dent Peninsula. Analysis by W. Vögtli.

Sp. 124: Hypersthene-andesite, augite-bearing, perlitic, amygdaloidal. NE. of Mt. Connor, SSW. of Simporna. Analysis by P. Bearth.

B. PLUTONIC ROCKS OF MOUNT KINABALU AND ASSOCIATED MINOR INTRUSIONS AND EXTRUSIONS

Kinabalu is the highest mountain in the Malay Archipelago, and the summit lies only 35 km. from the west coast of North Borneo and rises sheer from the foothills of the Crocker Range to a height of 4,100 m.

Mt. Kinabalu forms an outstanding landmark visible both from the Sulu Sea off Kuala Segama and from the China Sea off the Brunei coast. It also plays an important role in the folk-lore of the natives of North Borneo, as it is said to be the sacred resting place of departed souls.

The flora and fauna of Kinabalu have been studied by several naturalists in the past. The rocks, however, have never been the subject of a geological and petrological study, and those described in this paper were collected by W. Hotz and G. Niethammer in 1914–1915 and by E. Wenk in 1937 (see Appendix I).

Geology

Relationship between Morphology and Geology

Parallel to the west coast of North Borneo, and at a distance of 25–40 km. from the shore-line, runs the Crocker Range, the only major and persistent mountain chain in the country. This range, which is 1,000–2,000 m. high, has fairly sharp cross ridges and is in part deeply dissected, but it shows a pronounced summit plane which, in the neighbourhood of Mt. Kinabalu, reaches an altitude of about 2,000 m. From the even skyline of this mountain chain the lofty Gunong Kinabalu rises sheer and forms a high mountain massif crowned by numerous peaks and needles towering at least 2,000 m. above the highest elevations of the Crocker Range (see text Figs. 11 and 12 and Plate XVI, Fig. 2).

The morphology is in perfect accord with the geology. The Crocker Range is composed mainly of Tertiary sandstones and shales and, to a less extent, of pre-Tertiary sediments and ophiolites. Gunong Kinabalu, however, is a plutonic body of quartz-monzonitic composition* intruded into this steeply folded series and covers an area of roughly 100 sq. km. The contact zone between the igneous rocks and the surrounding country rocks forms the morphological base of the mountain. From this line the barren granitic rock walls of Gunong Kinabalu rise abruptly to form a characteristic dome-mountain. As is seen on Plate XVI, the convex flanks of the mountain do not converge in one dominating culmination but lead up to a fairly even crest connecting various summits of almost equal height. An unsolved mystery of Mt. Kinabalu is that this so-called " summit plateau ", of which only the western part does in fact possess the character of a plateau, has the form of a horse-shoe encircling a deep crater-like abyss situated in the central part of the massif. This abyss is, in its uppermost part, wide and of easy access from the " summit plateau ", but its lower part forms a deep and apparently inaccessible gorge drained by the Penataran River. As far as this chasm has been explored, it is found to be cut in plutonic rock and therefore has not the nature of a crater. Nothing further, however, can be said about the origin of this feature until the northern and eastern parts of

*For the sake of brevity the quartz-monzonitic intrusion of Kinabalu, which ranges from granodiorite to granite proper, is referred to as granitic in the following discussion.

Fig. 11. Sketch of Mt. Kinabalu, seen from SW.

After a sketch by E. Wenk. Jungle-clad country rocks (pre-tertiary sediments and ophiolites) in the foreground, mostly barren quartz-monzonitic rocks of the Tertiary Kinabalu intrusion in the background.

the massif have been explored. Fig. 1 of Plate XVI shows the view from Low's Peak, one of the western summits of Kinabalu, toward the eastern summits and down into the central abyss. Attention is drawn to the pronounced platy structure of the granite visible in the right-hand part of this picture. Exfoliation of the plutonic body parallel to the surface is seen also in Fig. 3 of the same plate.

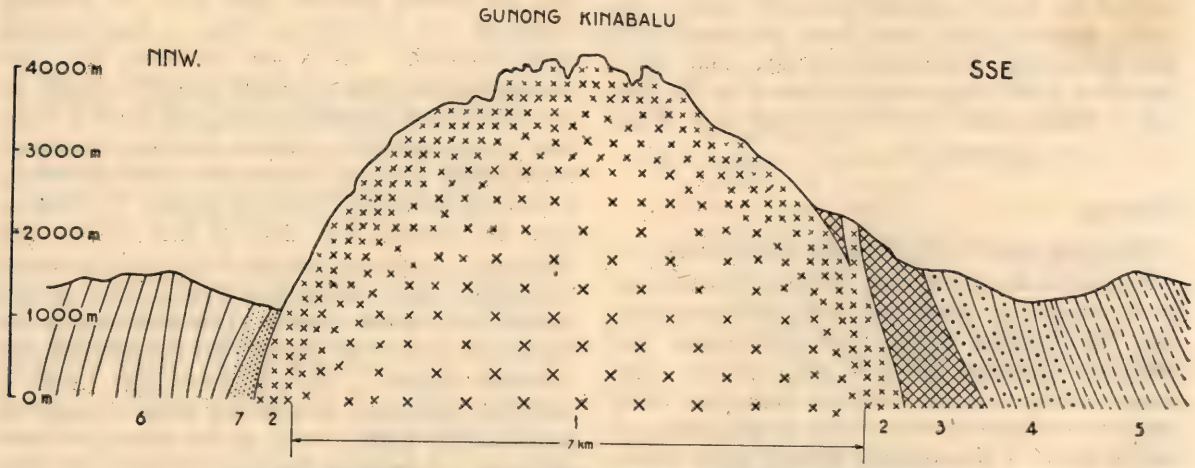


Fig. 12. Schematic section across the Tertiary intrusion of Gunong Kinabalu

1. **Coarse-grained quartz-monzonite and granodiorite**
2. **Micro-granitic and porphyritic border facies of 1**
3. **Peridotite of the Danau Formation;**
4. **Predominantly sediments of the Danau Formation**
5. **Slate Formation**
6. **Pre-Tertiary in general (unexplored)**
7. **Contact metamorphic zone of 6**

The light-coloured slabs shown on this picture consist of biotite-diopside-granodiorite-porphyry resting upon hornblende-biotite-micro-quartz-monzonite containing quartz-dioritic inclusions, which are rich in hornblende. This layered structure, which is the more conspicuous as the exfoliation coincides with it, is well developed in the marginal zone of the Kinabalu plutonic body. The platy parallelism is of primary origin and is believed to have been formed before the final consolidation of the rock.

The study of this marginal zone yielded some highly interesting geological results that are also of importance for the interpretation of the morphology. The porphyritic and more often microgranitic border of the intrusion was observed not only at the contacts with the wall rocks near the morphological base of the mountain, but also along the slopes and even on the " summit plateau ". In fact, only boulders, derived from the deep gorges and torrents, and blocks of the important scree deposits in the south-western part of the massif (S.Liwagu, near Ranau) show the typical coarse grain of the granite. The conclusion must be drawn that the present summit of Mt. Kinabalu is not much lower than the roof of the Kinabalu plutonic mass and erosion has had comparatively little effect on the granite itself. Gunong Kinabalu has not been chiselled and trimmed from a larger granitic trunk by erosional forces, but the country rock surrounding and covering the intrusion has been removed to such an extent that the plutonic body has been laid bare. This is proved also by the fact that, as far as the region has been explored, little granitic erosional material was found. Apart from that in S.Liwagu (near Ranau) and S.Kadamayan-Tampasuk (near Labong) granitic debris is definitely scarce.

In this connection the questions arise as to what thickness of previously overlying country rock has been eroded and at what depth the intrusion had consolidated. It is not likely that the granite moved upwards in relation to the wall rocks after consolidation because contact metamorphic rocks are found *in situ* and because no zones of crushed rocks or other signs of displacement occur along the contacts. In river outcrops to the west of Kinabalu, and at a horizontal distance of only 2,000 m. from the summit plateau, the contact between the intrusive body and the country rock is exposed at an altitude of only 1,000 m. (i.e. 3,100 m. below the summit, see Fig. 12). Above this contact a sedimentary cover must have existed whose top part was hardly lower than the summit and which thus had a thickness of at least 3,000 m. eroded since late Te times. This is a considerable amount, even if a strong general uplift of the whole north-western part of North Borneo be presumed.

Owing to the almost isoclinal folding of the Crocker Range, it is impossible to give any reliable figure for the thickness of the country rock previously overlying the top of the plutonic body. It may be anything from some hundreds to several thousands of metres. However, from a regional point of view, a sedimentary cover of as much as 2,000 m. above the roof of the Kinabalu plutonic body is highly improbable. More conclusive indications of a " shallow " level of consolidation of the granite are the slight traces of contact metamorphism, which point to a low-temperature intrusion congealed in the upper zones of the lithosphere. Such an origin is supported also by the many minor intrusions, dykes and sills, consanguineous with the Kinabalu quartz-monzonite and which are scattered around the major intrusion.

The space problem offered by the intrusion is not yet solved. Whatever the deep-seated origin of the Kinabalu quartz-monzonite may be, there is certainly no evidence of granitization *in situ* of the rocks previously occupying the space where the plutonic body now lies. The contacts are too sharp, the intrusive rocks too homogeneous and contaminations too feeble, to allow of such a conclusion. A diapyric intrusion displacing the strata encountered, combined with magmatic stoping, is more probable, especially as the indurated slates on the S. and W. flanks of the mountain dip away from the granite.

Rock Weathering

The problem presented by the scarcity of granitic rock-waste is intimately connected with that concerning the efficiency of mechanical disintegration and chemical decomposition by rock weathering. The rock samples collected from the surface of the mountain are very fresh. The feldspars and the mafic minerals (hornblende, biotite and diopside) are well preserved and rarely show signs of alteration due to weathering processes. Only the samples collected from below the tree limit, in the zone of the scrubby Leptospermum and moss forests below Paka cave (S. spur of Mt. Kinabalu), are to some degree weathered. Chemical weathering appears to be confined to the zone of vegetation encircling the basal part of the mountain. Mechanical weathering, active in the barren top part of the

granite massif, is due mainly to the effect of temperature changes. The changes in temperature of the surface rocks are quite considerable; at sunrise, in the summit region, the temperature of the air and of the surface rocks approaches freezing point, though it rarely falls below. During the morning hours the bare rock walls quickly become heated. At 10 a.m. the rock temperatures are such as to make climbing and walking barefoot definitely unpleasant. Before or after noon the daily rains rapidly cool the rock walls. The effect of changes in temperature must be the dominant factor in mechanical disintegration. It is far more important than the expansive force of ice, which forms only exceptionally on Mt. Kinabalu. In the Alps, on the other hand, and on other mountains situated in temperate or frigid latitudes, the importance of the two factors is reversed. It follows from the minor role of chemical weathering and mechanical disintegration caused by repeated freezing and thawing of water, that rock weathering must be a very slow process on Mt. Kinabalu. The granitic rocks are fresh, not because they are rapidly eroded, but because erosion is brought about almost exclusively by one factor, and also because the plutonic body has been exposed to erosion for only a short geological time. This comparatively minor importance of chemical weathering and mechanical disintegration explains also the scarcity of rock debris around Mt. Kinabalu.

Geological Occurrence, Contact Phenomena and Age

The Tertiary igneous rocks included in this chapter build up Mt. Kinabalu and compose also some minor intrusions and extrusions in the vicinity of the mountain. The rock samples collected derive from the following three different geological sites:

(1) Plutonic rock body forming the Kinabalu mountain massif.

(2) Minor intrusions occurring in the hilly country E. of Mt. Kinabalu, built up by Tertiary and pre-Tertiary formations.

(3) Sills or lava-flows in Tertiary sediments found in the coastal area W. and NW. of Mt. Kinabalu.

As outlined above, the plutonic rock body of Mt. Kinabalu displays some special morphological features. The minor intrusions, apophyses, dykes and sills connected with this major intrusion are not easily recognized in the field when judged exclusively from the geomorphological point of view. They are, however, of great geological interest, especially in connection with questions relating to the age of the intrusions. Enclosure VI shows the distribution of the known occurrences. It is evident from this map that only a small portion of the Kinabalu area has been covered by the geological surveys of Hotz, Niethammer and Wenk. Unfortunately this is true also for the Kinabalu massif proper, which has been explored only along its southern spur. Along this usual route of ascent (Tinompok-Paka cave-Gg. Kinabalu) the quartz-monzonite is in contact with fine-grained peridotitic rocks: harzburgite, dunite and actinolite-peridotite of the pre-Tertiary Danau Formation. In the field these rocks had been mistaken for hornfelses. Reinhard (see p. 91 in this paper) has drawn attention to the fact that serpentine is missing in these peridotites, while in all other occurrences of ultrabasic igneous rocks known in the Danau Formation of North Borneo the hydrous magnesium silicate is a common mineral constituent, and often the dominant one. Reinhard regards it as possible that the lack of serpentine and the fine grain of the Kinabalu peridotites are due to contact metamorphism by the quartz-monzonitic intrusion. The spilite-breccias, which are found as boulders in S.Kadamayan (see p. 90) and derive from the Danau Formation in contact with the Kinabalu plutonic body, are also altered by contact metamorphism. Their matrix, consisting of fine-grained chlorite, albite and calcite in the non-metamorphic types, has been recrystallized in the spilite-breccias SW. of Mt. Kinabalu and blue-green hornblende has been formed instead (see p. 91).

To the east of Mt. Kinabalu, especially in S.Makadau (tributary of S.Sugut), ophiolitic rocks of the Danau Formation are in contact with minor intrusions which are consanguineous with the Kinabalu quartz-monzonite; but such contact-metamorphic alteration of the basic rocks has not been noted here. The pre-Tertiary Slate Formation has so far not been observed in direct contact with the Kinabalu intrusion. However, the shales, slates and quartzitic sandstones of this formation, occurring in the south-western foothills of Mt. Kinabalu and adjoining the Danau Formation, are in part indurated and display a low-grade contact metamorphism. True hornfelses (prehnite-bearing biotite-plagioclase-hornfels) are found as boulders in S.Langanan, below Kuala Mamut (samples Nh. 476, 479); they appear to derive from the contacts between the pre-Tertiary Slate Formation and the Kinabalu intrusives, but the exact geological setting is not known. Far more important for the

dating of the Kinabalu intrusion are the occurrences of granodioritic and quartz-monzonitic rocks within Tertiary sediments, mapped by Niethammer in S.Merali, a tributary of S.Sugut. These minor intrusions and dykes are younger than the undivided group of sediments of Ta+b to Te age, and effected a low-grade metamorphic alteration of the Tertiary strata. The petrographical and petrochemical examination of these igneous rocks proved their consanguinity with the major intrusion of Mt. Kinabalu, which, as far as it has been explored, does not come into contact with the Tertiary strata. To the WNW. of Mt. Kinabalu, in the Tuaran river system, sills or possibly laccoliths of hornblende-biotite-granodiorite-porphyry were located within Tertiary sediments at Batu Lugas by Niethammer and in S.Mantaranau by Wenk. All these exposures of igneous rocks occur within the Tertiary sandstone-shale formation, which is characterized by red shales. This formation is foraminiferal in the southern part of the Kudat Peninsula, and there contains faunas of Ta-b and Te age as well as mixed faunal associations in which the old forms (Ta-b) are considered to have been reworked and redeposited in beds of Te age. In this formation another interesting occurrence of Tertiary volcanic rocks is reported by Niethammer from Tanjong and Pulau Sirar (SW. coast of Kudat Peninsula). Here augite-hornblende-andesite, showing columnar structure and being rich in inclusions of quartzite, slightly metamorphic quartz-sandstone and shale, is intercalated within the Tertiary sequence, together with andesitic agglomerate and beds and lenses of tuff. The sandstone layer situated at the bottom of the volcanic intercalation is indurated and ore-bearing. As a result of the low-grade contact metamorphism its content of foraminifera became clearly visible. Unfortunately the sample of this sandstone (Nh. 115) examined by Rutten (1925a) contained only operculina, which is not diagnostic. Rutten mentions, however, the lithological resemblance to samples from Tg. Loro (Kudat Peninsula, west coast) which are of Te age. With regard to the mineralogical and chemical composition, the hornblende-andesite from Sirar compares well both with rocks of the Kinabalu intrusion and with volcanic rocks from the east coast of North Borneo. Niethammer concluded from his observations that the Sirar andesites and volcanic agglomerates were roughly of the same age as the accompanying sediments, and that presumably they had been folded together.

This is not the case with the intrusive rocks of the Kinabalu area. Here, as mentioned above, the minor intrusions and dykes are younger than the formation as a whole, which is of Ta-e age. They occur within this formation, but are not found folded with the sediments and show no signs of mechanical deformation. The severe folding of the sediments took place in late Te times, and the intrusion can hardly be older than this date. Regional considerations, on the other hand, render it improbable that the intrusive rocks are much younger than late Te. From a regional point of view they are roughly of the same age as the volcanism on the east coast. It is probable that the Sirar andesite is somewhat older than the Kinabalu intrusives.

In the interior of North Borneo, about half-way between Mt. Kinabalu and the Simporna Peninsula on the east coast, porphyritic hornblende-microgranodiorites were found as boulders in S.Sinoa (right-hand tributary of S.Milian). A remarkable plutonic body of elliptical shape (Gg. Rara) was subsequently traced on aerial photographs in the head-waters of S.Sinoa (see Enclosure VII and Plate XX), and it appears that the samples found in S.Sinoa derive from this mountain. The rocks greatly resemble those of some minor intrusions situated in the surroundings of Mt. Kinabalu, and it is reasonable to assume a similar origin. The example of the remote Gg. Rara and its rocks shows also that many important geological features must have escaped the widely separated geological traverses.

Petrology

In spite of being situated in a tropical country, the intrusive rocks of Mt. Kinabalu and the surrounding area are surprisingly fresh and make an excellent subject for a thorough petrological and petrochemical study. In the following pages the mineral composition and texture of the representative rock types chosen for chemical analysis are described and the paragenetic relations are discussed, thus easily enabling the detailed data of this outstanding material to be used by other petrologists for purposes of comparison or general deductions.

1. Plutonic Rocks of Mt. Kinabalu proper

The plutonic body of Mt. Kinabalu is fairly homogeneous, and as far as the mineralogical composition is concerned, the rocks are rather uniform. There are, however, textural variations which characterize the transitions from the central into the marginal part.

The mafic minerals hornblende and, to a less extent, biotite form about 25% (19–37) by volume. All the samples collected contain a considerable amount of

quartz (13% to 27%). Plagioclase, showing pronounced oscillatory zoning (20% to 55% An), and zonal potash-soda feldspar occur in roughly equal proportions; in some rock types plagioclase is prevalent. The following modes (% by vol.) were determined with the aid of the Leitz petrographic integration table, and in this list two determinations of rocks from minor intrusions are included:

Rock sample	Nh. 411	Nh. 413	Wk. 66	Wk. 83	Wk. 84	Nh. 478	Nh. 481
	%	%	%	%	%	%	%
Quartz	14	17	13	27	18	16	19
Plagioclase	29	26	29	23	31	37	34
Potash-soda feldspar ..	33	34	21	27	31	22	28
Hornblende + ore ..	21	23	33	16	15	23	16
Biotite	3		4	7	5	2	3

These planimetric analyses show that the rocks examined belong to the family of the quartz-monzonites (Johannsen: adamellites, Lacroix: monzonite-granites), intermediate between granite proper and granodiorite, and that they include granodioritic types. All the rocks are holocrystalline and they show transitions from hypidiomorphic-granular to micro-granitic or porphyritic textures. Volcanic glass does not occur. Dark, fist-sized inclusions, consisting predominantly of hornblende, epidote, chlorite and prehnite, are found in the rocks of the marginal facies on the summit plateau. Some fine-grained aplite dykes, up to a foot thick, and joints with inch-long quartz crystals were observed in the summit region.

Rocks from the central part of the plutonic body

The following type-description refers to the hornblende-quartz-monzonite Nh. 411, the best representative of the coarse-grained rocks, which has been analysed chemically as have also two of its mineral constituents. These components are the same as those found in the medium-grained rock types, such as Wk. 66, 78, 83, 86 and H. 137, from which additional data are included. The exhaustive mineral description applies also to the rocks of the marginal type and of the minor intrusions, which will be discussed mainly from the point of view of their textural and chemical properties.

In the quartz-monzonite Nh. 411, the green-black hornblende prisms up to 1 cm. in length, the slightly reddish, almost rectangular potash-soda feldspars, some up to 3 cm. in length, and the many light-green idiomorphic plagioclase grains are easily recognized megascopically, and xenomorphic quartz is seen in the interstices between the other grains. The sample differs from most of the other Kinabalu plutonic rocks in the strikingly large size of its potash-soda feldspars; it is connected with granodiorite, however, through a large variety of textural and quantitative mineralogical transitions; in the granodiorites potash-soda feldspar occurs only in small grains in the interstitial matrix.

Texture: The first thing that strikes one in the thin-section picture is the presence of both idiomorphic and xenomorphic constituents. Distinctly idiomorphic are hornblende, biotite and plagioclase; in the last, the idiomorphism is often so highly developed that twinned crystals form re-entrant angles at the grain outline. The interstices are filled with quartz. In the same way the potash-soda feldspar is xenomorphic—contrary to what the megascopic examination would lead one to expect. The apparently rectangular crystals have, in fact, highly sinuate outlines, and the main mass of the potash-soda feldspar, together with quartz, forms the mesostasis. The relation between the acid marginal zones of the plagioclases and the potash-soda feldspars is discussed below. The rock is holocrystalline-hypidiomorphic, coarse to medium grained, and shows signs of having been crystallized in two successive stages. The sequence of crystallization is shown schematically in Fig. 13.

Mineral composition: The second microscopic characteristic of this and of all other Kinabalu plutonics is the typical evolution and composition of the plagioclases. Fresh and clear throughout, they are bounded mainly by the faces (010), (001), (110) and (100). They are tabular parallel to (010) and somewhat elongated parallel to the crystallographic a axis. The proportional dimensions in the direction of the crystallographic

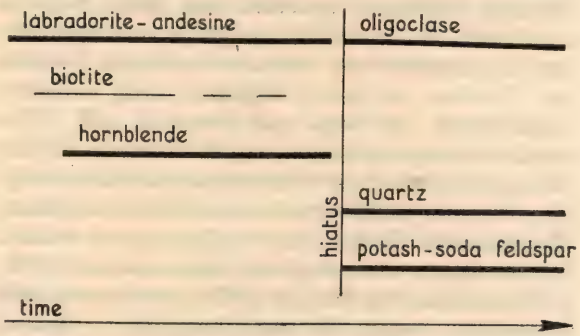


Fig. 13. The mineral succession in the quartz-monzonitic rocks of Mt. Kinabalu

axes a, b and c, found from a large number of measurements in orientated sections, are 2·1 : 1 : 1·8. The morphologically well-developed 010 face is at the same time the predominant composition-plane of the twinned individual crystals. All the grains are twinned; polysynthetic albite twinning is by far the commonest, often in combination with Carlsbad twinning and complex albite-Carlsbad twinning. Short pericline lamellae, occurring singly or polysynthetically, are widespread, while acline and Manebach twins are rare. Perfect (001) cleavage is ubiquitous and, together with

the intensive twinning, facilitates the mensuration and determination of the plagioclases by the universal-stage method. (100) and (110) cleavages are widespread, but as a rule imperfectly developed. The boundary planes (especially (100)) of the shell-like texture of the plagioclases may be brought into view much more accurately on the universal-stage; this texture is conditioned by the oscillatory zonal growth of the crystals.

After the idiomorphism, the most striking characteristic of the plagioclases of the Kinabalu plutonic rocks, and the one which really typifies them, is the oscillatory micro-zonal structure of its cores (see Plate IV, Fig. 2). These cores are hemmed round by a narrow acid marginal zone of normal zonal structure which is clearly demarcated from the central body. By linear measurement, this marginal zone occupies only 5% to 15% of the whole grain; but it takes up from 13% to 40% by volume, and this is of great importance in calculating the average anorthite content of the plagioclases. The central portions of the cores of the large plagioclase grains are as a rule the only parts of the crystals which are to any extent homogeneous. The anorthite content of these core centres in median sections of large grains is strikingly uniform at about 52% in Nh. 411 (varying from 55% to 49%). As we shall discover later, this ratio $\frac{An}{Ab+An}$ is also valid for the chemically analysed hornblende of this rock. One striking feature of the universal-stage measurements deserves mention here: apparently uniformly twinned plagioclase grains break down in the central core into separate aggregates of slightly different orientation. The twinning-lamellae and the indicatrix of these " islands " differ from each other by small amounts, whereas the surrounding zones are uniform. Where this phenomenon is developed to extremes, the central cores assume a peculiar speckled appearance. Starting from the labradorite cores, the anorthite content quickly falls to 40% or 32% and then suddenly rises to over 50%, often without any clear signs of resorption. After a narrow zone of this composition, another acid zone of andesine follows and so on. The central core of labradorite is thus surrounded by a series of closely fitting sheaths, only 1/100 to 1/10 mm. thick, which become more acid toward the exterior and then more basic, followed by frequent alternations of the two types. The plagioclases show an oscillatory-normal micro-zonal growth (Phemister, 1934) which appears particularly clearly in (010) sections. The micro-zonal texture is often so fine that in a transverse section of the grain over 1–2 mm. radial distance, more than 60 sheaths can be counted. The chemical composition of any sheath is not, however, so strongly differentiated from that of the others as the microscopic examination might lead one to suppose; it varies only between moderate limits (52% to 32% An). The fluctuation decreases slightly in intensity from the core toward the edge. However, examples have been met with in which intermediate sheaths may attain the anorthite value of the central core.

Outside the alternating sheaths of the plagioclase cores, which are bounded, on the whole, by straight lines often finely corroded in detail, there always follows, toward the edge of the grains, a hiatus of the first order: whereas the outermost sheath of the cores often still shows 40% to 46% An, the contiguous zone begins with about 32% and then falls steadily to 20% An. The plagioclase cores thus show oscillatory-normal zoning, while the marginal zones, which are well differentiated from the core, are of normal zonal growth.

The oligoclase zone does not always surround the plagioclase on all sides, and is rarely uniform. Hornblende grains may be in direct contact with the idiomorphic, oscillatory zonal plagioclase grains. On both sides of the hornblende, however, the oligoclase marginal zone is again contiguous to the core and, together with potash-soda feldspar and quartz, forms scalloped or denticulated sutures (see Plate IV, Fig. 2). In other grains it can be observed that the oligoclase margins are surrounded by a rim of potash-soda feldspar. It can therefore be deduced from the textural configuration that the normal zonal oligoclase marginal zones in Nh. 411, which are clearly differentiated from the oscillatory-zonal labradorite-andesine, crystallized at the same time as the quartz and potash-soda feldspars; the time of crystallization of potash-soda feldspar, however, outlasted that of plagioclase.

A further distinction between the core and the margin is that the cleavage and twin-lamellae are always much more highly developed in the core. The twin-lamellae often break off at the hiatus between core and margin or become lost in the inner part of the marginal zone. The breaking off of pericline lamellae at the core boundary was observed a number of times, particularly in corroded cores.

The oligoclase margins also have extremely abnormal optic axial angles, as the following data show:

Anorthite content determined by Fedoroff method:

25%, $-2V = 79°$	28%, $-2V = 72°$
27%–28%, $-2V = 75°$	30%, $-2V = 74°$
28%, $-2V = 80°$	34%, $-2V = 89°$

In other Kinabalu plutonic rocks the oligoclase margins of plagioclases with analogous zonal growth yielded similar values:

Wk. 66: anorthite content determined by Fedoroff method:

23%, $-2V = 75°$	27%–28%, $-2V = 82°$
27%, $-2V = 74°$	30%, $-2V = 74°$
27%, $-2V = 84°$	

The same in *Wk.* 64:

Even though the determination of the optic axial angle is always rather unreliable, a definite tendency nevertheless is expressed in these values. It may be presumed that these oligoclases with abnormal optic axial angles are rich in potash; a potash enrichment in the residual magma of these rocks has been proven by chemical analysis (see Fig. 1 in Wenk, 1945b).

The following data afford evidence that the anorthite content of the plagioclase series shows about the same variation in the rocks of the Kinabalu massif as in

those of the related minor intrusions and extrusions (determinations by universal-stage methods):

Kinabalu massif		*Minor intrusions and extrusions*	
rock sample	An content	rock sample	An content
Wk. 64	28%–52%	Wk. 5	32%–50%
66	18%–60%	6	28%–42%
67	50%	Nh. 105	40%–85%
69	43%	417	22%–55%
78	40%–47%	422	60%–65%
83	32%–55%	423	48%–58%
84	42%–47%	424	42%–47%
85	50%	470	43%–50%
H. 133	47%–49%	473	50%–58%
Nh. 411	20%–55%	481	53%
413	35%–39%		
414	56%–60%		
478	45%–50%		

Potash-soda feldspar, on the one hand, forms crystals up to 3 cm. in length with almost rectangular boundaries and finely scalloped outlines, and on the other hand fills the interstices; also, in some cases, it borders grains of plagioclase. It is always somewhat dusty, and for this very reason easily distinguishable in thin section from the clear plagioclase. The fine dust-like particles are sometimes arranged in stripes; perthitic immiscibility is not, however, perceptible. The large crystals are twinned according to the Carlsbad law. A very fine polysynthetic twinning on (15;0$\bar{2}$) is perceptible only in orientated sections and with powerful magnification; microclinic cross-hatching is absent. The crystals cleave excellently along (001), not so well along (010), nor along the faces (100) and (15; 0$\bar{2}$). Basal pinacoid sections show an angle of extinction of 8°–10° between n_γ and the micro-striation along (15; 0$\bar{2}$). Revolving-stage measurements confirm what had already been determined by ordinary methods, namely, that n_γ never coincides with the (010) pole. The angle between n_γ and the (010) pole was in several cases measured at 9°. The poles of (001) and (15; 0$\bar{2}$) also deviate distinctly in every case from the optic plane of symmetry $n_\alpha n_\beta$; they fall within a great circle which forms an angle of 8°–10° with the plane $n_\gamma n_\beta$. All the closely examined grains are thus triclinic.

Reliable measurement of the position of the indicatrix of the potash-soda feldspar grains on the universal-stage can often be performed only with the greatest difficulty, when the optic plane of symmetry $n_\beta n_\gamma$ lies close to the plane of the thin section. When the optic axes of symmetry n_β and n_γ are brought in approximate coincidence with the K-axis of the stage (horizontal E–W. axis), the grains remain dark over a wide range of the angles n and h. It may be presumed that a sub-microscopic twinning after the face (15; 0$\bar{2}$), which runs in the vicinity of the plane $n_\beta n_\gamma$, is responsible for this phenomenon. Sections perpendicular to this plane of polysynthetic lamellation can be more easily measured optically.

The large potash-soda feldspar grains show distinct zonal growth. Their broad marginal zones, like the potash-soda feldspars filling the interstices and like the alkali-feldspar margins which occasionally surround the plagioclase, are comparatively uniform, while the central cores exhibit rapidly changing optical properties. The cores of the large alkali-feldspars have optic axial angles of — 60° to — 50°, while the marginal zones show angles of — 48° to — 42°. In rock Wk. 66, five measurements of optic axial angles revealed — 2V = 37°, 42°, 42°, 44° and 46°; no higher values were ascertained here. In (001) cleavage flakes, n_α was determined as 1·520 (core) to 1·5215 (marginal zone) and n_γ as 1·525 (core) to 1·526 (marginal zone). These optical data suggest that the cores are richer in Or than the marginal portions. The pronounced zonal texture cannot be attributed to alternating physical conditions (high temperature optics). The chemical analysis of the mineral (see Table IV) shows the mean composition of the potash-soda feldspar to be 71 Or 29 Ab.

Hornblende is the dominant mafic constituent. It forms prisms up to 10 mm. long and is idiomorphic throughout. The smaller hornblende grains, associated with biotite, occasionally form glomero-granular clusters. In other rock types, especially those of the marginal facies, this feature is more pronounced and may pass into the formation of megascopical dark spots. Sometimes the hornblende prisms are poikilitic and include small flakes of biotite, grains of plagioclase, magnetite and more rarely apatite and zircon.

Pleochroism: n_α greenish yellow
n_β yellowish green
n_γ dark olive green.

Zonal growth is not very distinct in the sample Nh. 411, but in other specimens it is marked by concentric zones of slightly different colour. In the central part of the zonal grains n_γ has a brownish tint. Lamellar twinning on (100) is common, and twinning on (001) is also occasionally observed. By measuring the orientation of the indicatrix and the cleavage planes of the hornblende on the Fedoroff stage in Na-light and by constructing the c axis, the following results were obtained in the sample described and in associated coarse- to medium-grained rocks:

Sample	$n_\gamma \wedge c$	— 2V (Na-light)
Nh. 408	15°	67°, 68°
Nh. 411	15° (average of 4 determinations)	60°, 64·5°, 65°
Nh. 478	17°	65·5°, 67°, 67°
Wk. 66	16·5° (average of 5 determinations)	69°, 69°, 68°
Wk. 78	17·5°	66·5°, 67°

In the olive-brown and brown hornblendes of the rocks from the minor intrusions, the extinction angle is smaller (10°–11°) and 2V varies from — 73° to — 85°. In cleavage flakes (Nh. 411) n_α' was determined as 1·6715 (+0·001) by the dispersion method. Owing to strong pleochroism n_γ could not be determined satisfactorily. $n_\gamma - n_\alpha = 0{\cdot}019$.

The hornblende of sample Nh. 411 was chemically analysed by J. von Steiger. The calculation according to Warren's (1930) formula $(OH, F)_2$ (Na, Ca, K)$_{2-3}$ (Mg, Fe″, Fe‴, Ti. Mn, Al)$_5$ ((Si, Al)$_8$ O_{22}), derived

from a study of the crystal structure of tremolite, and extended to include the common hornblendes, gives the following result:

Hornblende from quartz-monzonite Nh. 411

	% by weight	No. of metal atoms on a basis of 24 (O, OH, F)	
SiO_2	42·69	6·40	8
Al_2O_3	10·88	1·92 (1·60 + 0·32)	
V_2O_3	0·19	0·03	4·95
TiO_2	1·53	0·17	
Fe_2O_3	3·95	0·45	
FeO	14·15	1·78	
MnO	0·32	0·04	
MgO	9·67	2·16	
CaO	12·19	1·96	2·71
Na_2O	1·82	0·52	
K_2O	1·21	0·23	
H_2O+	1·71	1·84	1·84
H_2O-	0·10		
F	—		
	100·41	sp. gr. = 3·26	

It is a well-known fact that common hornblende has a wide range of composition. In Table VI the chemical composition of the Kinabalu hornblende is compared with related hornblendes selected from the large number of amphiboles analysed in the past. Attention is drawn to the remarkable agreement between the figures of columns 1 and 2 of this table. Of the very few Indonesian amphiboles analysed, the types listed as 2 and 3 agree very well with the Kinabalu hornblende, which appears to possess a chemical composition characteristic of this area. Graphical representation of the hornblende and of various rocks from the Kinabalu area shows (see p. 60) that the chemical composition of this mineral cannot vary much in the different rock types.

Biotite occurs in minor quantities and only in the form of small flakes. The mineral is strongly pleochroic (yellowish, black-brown). Accessory minerals are magnetite, rutile, apatite and zircon.

The conditions for co-existence between hornblende, biotite, plagioclase and potash-soda feldspar in the quartz-monzonite Nh. 411 have been discussed in detail by Wenk (1945 b, op. cit. pp. 142–145 and 149–152).

By the Niggli (1936) molecular norm, superseding the American C.I.P.W. weight norm, the mineral composition of the quartz-monzonite Nh. 411 can easily be calculated on the basis of the chemical rock analyses as well as of the two mineral analyses (see molecular norms in Table V) and in agreement with the observed mineral composition. Since hornblende is the only mineral component containing Cs, the first step in the calculation is to apportion as much hornblende of the known chemical composition as conforms with the amount of Cs in the rock. The remaining M components (Fo, Fa, Fs) make up magnetite and biotite in accordance with the theoretical composition of these minerals. The calculated mg-value of the biotite (0·55) does not quite correspond with that to be expected in a lepidomelane-like mica; but this is due to the minor amounts of Fo and Fa available. From the remaining L and Q potash-soda feldspar of the proven chemical composition is first apportioned and then plagioclase and quartz.

Cp	Ru	Kp	Ne	Cal	Cs	Fo	Fa	Fs	Q	
0·4	0·4	17·2	18·3	7·9	2·7	5·3	4·5	1·3	42·0	quartz-monzonite Nh. 411
	0·2	0·9	2·1	2·3	2·7	4·3	3·5	0·9	3·6	20·5% hornblende
							0·2	0·4	+0·2	0·4% magnetite
		1·1	0·1			1·0	0·8		0·2	3·2% biotite
		14·1	5·8						13·2	33·1% potash-soda feldspar Or 71 Ab 29
		1·1	10·3	5·6					11·3	28·3% plagioclase Or 6·5 Ab 60·5 An 33
	0·2								13·9	13·9% quartz
0·4										0·2% rutile 0·4% Cp (apatite)
0·4	0·4	17·2	18·3	7·9	2·7	5·3	4·5	1·3	42·0	100%

These figures are in excellent agreement with the modal composition and prove the efficiency of the Niggli molecular norm calculation. The calculated composition of the plagioclase (Or 6·5 Ab 60·5 An 33) also agrees with the modal anorthite content (20%–52%), if the influence of the oligoclase marginal zone upon the average composition is duly taken into consideration (15% in linear direction = 40% by vol.).

TABLE VI. WEIGHT PERCENTAGES AND NIGGLI VALUES OF THE KINABALU HORNBLENDE AND RELATED TYPES

	1	2	3	4	5	6	7
	Kinabalu N. Borneo	P.Belang N. Celebes	Pengaron Borneo	Garabal Scotland	Glen Tilt Scotland	Wald-viertel Austria	S.Cristo-bal Colorado
SiO_2	42·69	42·57	42·40	41·61	42·11	42·80	43·95
Al_2O_3	10·88	11·62	10·88	12·16	10·05	11·31	11·40
Fe_2O_3	3·95	6·86	6·26	4·04	2·82	4·13	4·69
FeO	14·15	12·50	9·42	12·05	15·14	14·61	9·02
MnO	0·32	0·38	—	tr.	0·24	0·17	0·14
MgO	9·67	9·82	10·02	11·44	11·48	8·81	13·73
CaO	12·19	11·83	14·20	11·63	11·34	13·88	11·12
Na_2O	1·82	1·67	1·53	1·85	1·01	1·11	2·08
K_2O	1·21	1·04	tr.	0·58	1·43	1·08	0·86
TiO_2	1·53	0·78	—	2·57	2·76	1·59	1·81
P_2O_5	—	—	—	—	—	—	—
V_2O_3	0·19	—	—	—	—	—	—
H_2O+	1·71	1·21	loss on ignition	2·33	2·02	0·51	0·79
H_2O-	0·10	—	5·43	0·21	0·06	—	—
	100·41	100·28	100·14	100·47	100·46	100·00	99·59
si	83	81·5	84	80	81	82·5	83·5
al	12·5	13	12·5	14	11·5	13	12·5
fm	57·5	58	54·5	58	62	55	60
c	25	24·5	30	24	23·5	29	22·5
alk	5	4·5	3	4	3·5	3	5
Q	17·7	17·9	20·3	17·6	17·5	19·3	17·8
L	25·8	26·2	23·6	26·8	22·6	24·2	25·9
M	55·4	55·3	56·1	53·8	57·9	55·4	55·0
Ru	1·1	0·6	—	1·8	2·0	1·1	1·3
π	·43	·50	·62	·54	·51	·58	·45
K	·30	·29	?	·17	·48	·39	·21
γ	·24	·21	·27	·20	·20	·26	·20
mg	·49	·48	·54	·56	·52	·46	·65

1. green hornblende from quartz-monzonite Nh. 411, Gunong Kinabalu, North Borneo. J. von Steiger, analyst.
2. common hornblende from andesitic rock (with magnetite inclusions, slightly altered), Pulang Belang, Minahassa, North Celebes. W. Kunitz N. Jahrb. Min. B.B. Vol. 60, 1930, pp. 206, 207. W. Kunitz, analyst.
3. hornblende from andesite (analysed), Pengaron, South Borneo. R. D. M. Verbeek: Jaarb. Mijnw. Ned. O. Indië, Vol. 4, No. 1, 1875, p. 3. A Frenzel, analyst.
4. green-brown hornblende from diorite, Garabal Hill-Glen Fyne Complex, Scotland. S. R. Nockolds: Quart. Journ. Geol. Soc. London, Vol. 96, 1940, p. 490. S. R. Nockolds, analyst.
5. hornblende from diorite, Glen Tilt, Perthshire, Scotland. W. A. Deer: Min. Mag., Vol. 25, 1938, p. 58. W. A. Deer, analyst.
6. green hornblende (pyrite and titanite deducted) from amphibolite (analysed), Schlossberg, near Spitz, niederösterreichisches Waldviertel, Austria. A. Marchet: Min. Petr. Mitt., Vol. 38, 1925, p. 494. A Marchet, analyst.
7. green hornblende from andesite dyke cutting Potosi volcanics, SE. corner of San Cristobal quadrangle, Colorado. E. S. Larsen, J. Irving: Am. Min., Vol. 22, 1937, p. 897. F. A. Gonyer, analyst.

As is shown by the following calculation, the same procedure can easily be applied to other rock types of Mt. Kinabalu (e.g. Wk. 66), and this proves that the chemical composition of the minerals is much the same throughout the plutonic body:

Cp	Ru	Kp	Ne	Cal	Cs	Fo	Fa	Fs	Q	
0·7	0·4	11·6	20·2	7·7	4·4	7·7	5·6	3·5	38·2	granodiorite Wk. 66
	0·4	1·4	3·5	3·5	4·4	6·8	7	1	5·8	32·9% hornblende
							0·3	0·6	+0·3	0·6% magnetite
		1·1	0·2			0·9	1	1	0·2	3·5% biotite
		8·6	5·7						9·5	23·8% potash-soda feldspar Or 60 Ab 40
		0·5	10·8	4·2					10·4	25·9% plagioclase Or 3 Ab 70 An 27
									12·6	12·6% quartz
0·7										0·7% Cp (apatite)
0·7	0·4	11·6	20·2	7·7	4·4	7·7	9	1	38·2	100%

Only the composition of the feldspars differs slightly from that found in sample Nh. 411. The calculated Or content of the potash-soda feldspar Wk. 66 amounts to 60% (71% in Nh. 411), but this result is supported by the very small — 2V angle (37° to 46° in Wk. 66, as compared with 42° to 60° in Nh. 411).

Rocks from the marginal zone of the plutonic body

All the plutonic rocks exposed along the south spur of the mountain belong to the marginal facies of the plutonic body. This applies to all the samples deriving from the basal contact zone between Kamburanga and Paka up to the summit plateau. Only the rocks of the summit peaks and boulders derived from the narrow, deep-cut gorges of the mountain massif are medium- to coarse-grained and show characteristic plutonic textures. It is this fact which leads to the geologically interesting conclusion that the summit pleateau represents the slightly eroded roof of the plutonic body.

Because of the poor exposures, and particularly on account of the weathering of the marginal facies of the quartz-monzonitic rocks at their contact with the peridotites lying in the thick belt of vegetation, the textural transitions from coarse-grained to medium- or fine-grained, microgranitic to porphyritic rocks can more easily be studied on the summit plateau. It must, however, be stressed that the phenomena are identical in both places.

Hornblende bearing rocks

These form by far the greater part of the marginal facies. Qualitatively they have the same mineral composition as the core types, but are often richer in dark components. All textural transitions can be discerned from the coarse to medium grained rocks described above to the microgranitic and porphyritic rocks which occur also in the minor intrusions in an identical form.

A. TRANSITIONS TO MICROGRANITIC BORDER FACIES

Examples from summit plateau: thin section series Wk. 66, H. 137, Wk. 84, Wk. 68, Wk. 85, Wk. 72, Wk. 64.

Examples from Paka area: thin sections H. 133, H, 133a, Wk. 73.

Megascopically, the transitions are characterized by the progressive formation of a microgranular groundmass in which all the mineral components are concerned. At the same time, however, larger and idiomorphic plagioclase, hornblende and biotite crystals are always present. But as gradual transitions are present, from plagioclases, hornblendes and biotite flakes measuring several millimetres down to micro-granules, we cannot speak of a " porphyritic " texture but shall, in accordance with the usage of French petrographers, use the term " microgranitic ". The minerals of the coarser-grained microgranitic rocks can still be recognized by the naked eye; the rocks, however, merge into types which, due to their fine grain, are finely speckled black and white, thus appearing darker to the eye, and whose components can be recognized only with the hand-lens.

The microphotographs of Plate V demonstrate these gradual transitions better than any description. It is evident that some larger and idiomorphic hornblende and plagioclase crystals persist even in the most fine-grained varieties. The potash-soda feldspar in Fig. 3 of this plate is poikilitic in the marginal zone and includes small grains of plagioclase, quartz, biotite and hornblende. The biotite has peculiar resorbed contour lines and may form skeleton crystals. Characteristic of the rocks of the marginal facies are the accumulations of fine-grained hornblende and biotite in irregular patches, as mentioned above, and also the small flakes of biotite which, being irregularly distributed and arranged within the large single crystals of hornblende, give them a speckled appearance.

B. PORPHYRITIC BORDER FACIES

Typical porphyritic rocks in which the phenocrysts are easily distinguishable from the groundmass were collected only in S.Liwagu (Labuk) as blocks derived from the southern part of Mt. Kinabalu. In these rocks (Nh. 407, 408) large phenocrysts of potash-soda feldspar, showing Carlsbad twins, as well as plagioclase, hornblende and biotite-chlorite occur in a very fine-grained matrix composed of the same minerals plus quartz.

Diopside-bearing rock

Only one diopside-bearing rock, a diopside-biotite-granodiorite-porphyry, has been collected (Wk. 69) below the summit plateau of Kinabalu. Modal composition: 11% diopside ($c \wedge n_\gamma$ 38°, +2V 60°, $n_\gamma - n_\alpha$ 0·029), 6% biotite, 20% plagioclase, 4%

potash-soda feldspar, 2% ore, 57% quartz-rich groundmass. The occurrence of diopside instead of hornblende is an interesting exception to the general rule. If the water content be disregarded, diopside might also have been formed in the other rock types, as is shown by the following result of a calculation with the aid of Niggli molecular norms, using the analysed hornblende-quartz-monzonite Nh. 411 as an example:

mode of hornblende rock Nh. 411		mode of heteromorphic diopside variant (calculated on the base of the chemical composition of rock Nh. 411)
20·5%	hornblende	—
—	diopside	8·6%
3·2%	biotite	10·1%
33·1%	potash-soda feldspar	30·0%
28·3%	plagioclase	35·5% (An 38 Ab 62)
13·9%	quartz	13·8%
0·4%	magnetite	1·2%
0·2%	rutile	0·4%
0·4%	Cp (apatite)	0·4%

This example of rock heteromorphism shows that the occurrence of pyroxene instead of hornblende entails a considerable increase in biotite and plagioclase and a decrease in potash-soda feldspar. In the hornblende-bearing rock potash-soda feldspar is the dominant feldspar; in the diopside variant, however, plagioclase predominates and is, moreover, richer in anorthite (38% An) than that of the heteromorphic hornblende-quartz-monzonite (33% An).

2. Minor Intrusions and Extrusions

Enclosure VI (see also Appendix I) shows the distribution of the minor intrusions, occurring in the area to the E. and SE. of Mt. Kinabalu, at the headwaters of the S.Sugut. Among the outcrops of Tertiary igneous rocks scattered in this region, the rocks of Bt. Oisapad, 18 km. E. of Mt. Kinabalu (samples Nh. 477 and 478) appear to be directly connected with the main intrusion. From this locality derive the only medium to coarse-grained rocks found in the less immediate neighbourhood of Mt. Kinabalu. Unfortunately the intermediate area between Gg. Kinabalu and Bt. Oisapad has not yet been explored, and the assumed existence of the extensive eastern spur of Mt. Kinabalu has not yet been verified. The minor intrusions proper are separated from the main plutonic body by pre-Tertiary sediments, ophiolites and Tertiary sediments. Their rocks show either porphyritic or micro-granitic texture and resemble the rock types found in the marginal facies of the Kinabalu plutonic body. With few exceptions, the mineral constituents of the minor intrusions agree with those described in the preceding pages. Among the mafic minerals, hornblende and biotite remain the predominant constituents; biotite is rather more important than in the rocks of Mt. Kinabalu. Hypersthene, augite and in some cases garnet may also occur in minor amounts; these three minerals were not observed in the rocks of Mt. Kinabalu. Plagioclase is the prevalent feldspar. Potash-soda feldspar is nearly always present, but mostly confined to the groundmass. The rocks of the minor intrusions are predominantly granodiorites, to a lesser extent quartz-monzonites, and more rarely quartz-diorites and tonalites; whereas, as shown above, the Kinabalu plutonic body is composed essentially of quartz-monzonites, ranging from granite proper to granodiorite. The high potash content of the rocks is, in the minor intrusions, occasioned by the considerable percentage of biotite (10%–15%) in combination with potash-soda feldspar; in the rocks of Gg. Kinabalu it is due to the predominance of potash-soda feldspar and minor amounts of biotite. As the rocks of the main plutonic body and those of the minor intrusions have approximately the same chemical composition, the hornblende-quartz-monzonites of Mt. Kinabalu and the pyroxene-bearing biotite-hornblende granodiorites of the surrounding area may be regarded as being almost heteromorphic, similar to the example calculated and discussed on this page. Notwithstanding the minor differences mentioned, the rocks of the Kinabalu mountain massif are connected with those of the minor intrusions by numerous transitions. Megascopically and microscopically they form a unit.

As the mineralogical composition and texture of the rocks of the minor intrusions have already been mentioned in the preceding chapter on the plutonic rocks of Mt. Kinabalu proper, only a brief description will be given here of the three representative rock samples which have been chemically analysed:

Nh. 473: *hypersthene-bearing hornblende-biotite-quartz-gabbro-diorite-porphyry* = tonalite-porphyry; SW. of Paranchangan (Sugut); minor intrusion in Tertiary strata. Phenocrysts of olive-green hornblende, showing zonal structure ($-2V = 71°–75°$ (core) and 85° (margin); $c \wedge n_\gamma = 10°–11°$ (core) and 15° (margin), dark-brown biotite, plagioclase 58%–50% An) and hypersthene ($-2V = 53°–56°$) with gradual transition to the quartz-bearing groundmass. Mode (estimated): hornblende 20%, biotite 8%, hypersthene 2%, plagioclase 46%, quartz 20%, potash feldspar 4%.

Nh. 417: *porphyritic hornblende - biotite - micro - granodiorite* from Bukit Kargan, SSE. of Paranchangan (Sugut); minor intrusion in pre-Tertiary rocks. Phenocrysts of olive-brown hornblende ($-2V = 80°–82°$; $c \wedge n_\gamma = 11°$), dark-brown biotite and plagioclase showing oscillatory zoning (55%–22% An) in an equigranular, quartz-bearing and potash-soda feldspar-bearing groundmass. Mode: hornblende 16% by vol., biotite 10%, plagioclase 15%, groundmass 59%.

Nh. 422: *augite- and hypersthene-bearing biotite-hornblende - granodiorite - porphyry;* below Kg. Tadul, S.Merali (Sugut); minor intrusion in Tertiary strata. Phenocrysts of yellow-brown biotite, clove-brown hornblende ($-2V = 73°–83°$, $c \wedge n_\gamma = 11°$), augite, hypersthene and altered plagioclase (65%–60% An) in a very fine-grained, potash-soda feldspar-bearing groundmass, rich in andesine-labradorite and quartz. Mode (estimated): biotite 15%, hornblende 8%, augite and hypersthene 5%, plagioclase, potash-soda feldspar and quartz 72%.

Analogous rocks occur also in the area of Tuaran, WNW. of Mt. Kinabalu (samples Nh. 255, Wk. 75, 76). It may be mentioned here that porphyritic hornblende-micro-granodiorites (Wk. 5–9), very similar to those of the Kinabalu region, were collected as pebbles on the gravel banks of S.Sinoa (southern tributary of the Milian River, interior). They appear to derive from Gg. Rara, a remarkable mountain of elliptic shape traced on aerial photographs in the head-waters of S.Sinoa (see Plate XX and Enclosure VII).

Along the upper course of S.Merali (SE. corner of Enclosure VI) several samples with the texture of extrusive rocks were collected by Niethammer. According to the diaries of this geologist they occur as sills and dykes cutting through the Tertiary and pre-Tertiary formations. They represent biotite-rhyodacites and biotite-hornblende-rhyodacites rich in alumina; one sample (Nh. 474) even contains garnet. A representative type, the biotite-rhyodacite Nh. 424, of granodioritic composition, was chemically analysed. A microphotograph of a similar rock (Nh. 423) is shown on Plate IV, Fig. 1.

Nh. 424: *biotite-rhyodacite;* S.Merali below Kuala Bawain (head-waters of S.Sugut; dyke cutting through the Danau Formation. Large phenocrysts of plagioclase (47%–42% An) and corroded quartz, minor phenocrysts of yellow-brown biotite in a fine-grained, slightly flow-textured matrix bearing quartz, potash-soda feldspar, sericite and carbonate. Mode (estimated): plagioclase-phenocrysts 25%, quartz-phenocrysts 15%, biotite 10%, matrix 50%.

Conclusive evidence for the extrusive character and volcanic origin of Tertiary igneous rocks was found by Niethammer on the SW. coast of the Kudat Peninsula, at Tanjong and Pulau Sirar (65 km. N. of Gg. Kinabalu). Here hornblende-andesites, showing columnar structure, are associated with andesitic crystal-tuffs which are rich in hornblende and with volcanic agglomerates. From this outcrop, described on p. 51, the samples Nh. 105–108, 113, 118–127 are derived, of which Nh. 105 was subjected to a chemical analysis.

Nh. 105: *pyroxene-bearing hornblende-labradorite-andesite* from western part of Tg. Sirar (SW. Kudat Peninsula). Phenocrysts: plagioclase 26·5% 85%–57% An), olive hornblende 10% ($-2V = 73°–76°$; $c \wedge n_\gamma = 19°–20°$), hypersthene and augite 2·5%, magnetite 2%. Groundmass 59% (plagioclase microlites 66%–40% An). In respect of mineralogical and chemical composition, the rocks from Tanjong Sirar are comparable both with the Simporna volcanic rocks (east coast) and with the Kinabalu intrusive rocks (west coast). It appears that a zone, characterized by Tertiary magmatic activity, extends in a NW.–SE. direction (SW. Kudat Peninsula-Gg. Kinabalu-Gg. Rara (S. Milian)-Simporna Peninsula) right across North Borneo.

3. Chemical Composition

Eight different rock types from various parts of the Kinabalu massif and the minor intrusions were selected for chemical analysis. The results of the chemical examination carried out by P. Bearth and J. von Steiger are set out in Tables IV and V. Surprisingly enough, the results of the analysis of the samples Nh. 417, 422, 473 and Wk. 66, whose rock-names and places of origin can be found in Table IV, agree very closely with each other. This circumstance is of particular importance owing to the fact that rock Wk. 66 comes from the summit of Mt. Kinabalu, whereas the other samples are derived from minor intrusions E. of the mountain (see Enclosure VI). From this it follows that these minor intrusions agree, not only mineralogically and petrographically, but also petrochemically, with the main rock of the Kinabalu mountain stock, and are consanguineous with this body. We are evidently dealing here with a chemical composition which is characteristic of the igneous rocks of the Kinabalu intrusion. The average Niggli values from the four samples mentioned are as follows (comparative values for Niggli's monzonite-dioritic magma type are shown in brackets):

si	191·5	(135)
al	28	(27)
fm	37	(38)
c	19·5	(21·5)
alk	15·5	(13·5)
k	0·44	(0·4)
mg	0·50	(0·5)

Apart from si, these mean values are in close agreement with the monzonite-dioritic magma type. This chemical composition may be regarded as characteristic for the slightly femic Kinabalu rocks; while the data contained in Table V in respect of the representative coarse-grained rock Nh. 411 of the Kinabalu mountain stock may be considered characteristic for the slightly salic members. This latter rock occupies an intermediary position between the quartz-monzonitic (potash series) and the opdalitic magma types

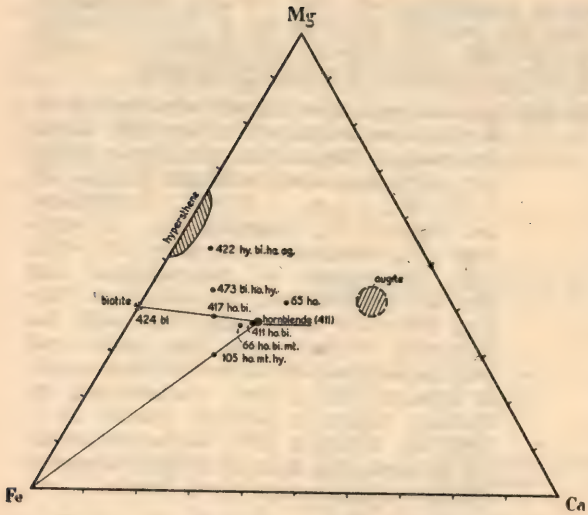


Fig. 14. Mg-Ca-Fe diagram of the Tertiary igneous rocks of Mt. Kinabalu

Rock samples Nh. 105, 411, 417, 422, 424, 473 *and Wk.* 65, 66 *(dots); hornblende from quartz-monzonite Nh.* 411 *(encircled dot).*

bi = biotite, ho = hornblende, hy = hypersthene, ag = augite, mt = magnetite.

(calc-alkali series). The most widespread rock types, therefore, correspond chemically to the monzonite to potash-diorite types, rich in silica, in close agreement with the mineralogical classification. The three remaining rocks which have been chemically analysed (Nh. 105, 424, Wk. 65) occur only locally, and evidently represent special varieties. In the rhyodacite Nh. 424 there is a striking surplus of alumina (al — (c+alk) = 3·5), which may even be considerably larger in a few rare, related garnet-bearing types (Nh. 448, 474). The magma of these peralic rocks, all of which occur as localized, often dyke-like bodies, might have been contaminated through the assimilation of argillaceous material.

The chemical composition of the andesite Nh. 105 from the Tg. Sirar, 65 km. north of Gunong Kinabalu, differs somewhat (al > fm with si 164, dioritic) from the Kinabalu rocks; but on the other hand this sample fits admirably into the variation graph of the east coast volcanics (Fig. 9).

Fig. 14 gives an excellent insight into the relations between the chemical composition of the rock as well as the rock-forming minerals and the mode of the rocks. This graph shows the distribution of Mg (Fo), Fe (Fa, Fs) and Ca (Cs), which are combined with SiO_2, in the mafic minerals and in the various rocks. The projection point of the hornblende in rock Nh. 411 is obtained from the results of chemical analysis. That

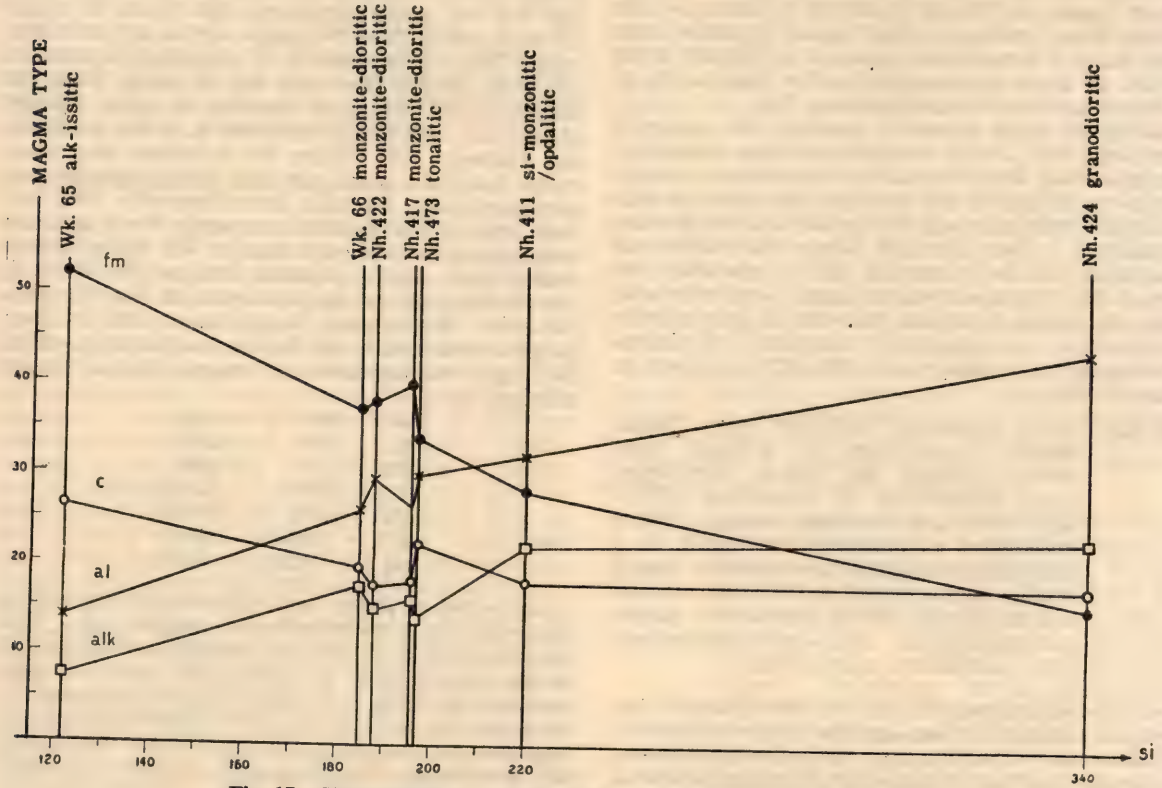


Fig. 15. Variation diagram of the Tertiary igneous rocks of Mt. Kinabalu

For explanation see Fig. 9, *page* 40.

of the biotite must agree with the projection point of rock Nh. 424, which has no other dark constituents besides biotite. If the Fo-Fa/Fs-Cs composition of biotite and hornblende were to remain approximately equal in the various analysed rocks of the Kinabalu intrusion, the rock-bearing hornblende and biotite must lie on the straight line " biotite-hornblende "; while the varieties which also bear magnetite besides these two constituents should fall in the field below this straight line, and those bearing hornblende, biotite and hypersthene above the " biotite-hornblende " line. This is, in fact, the case, as is shown by the mineral-composition data against the various rock numbers in the graph. The relative amounts of the dark constituents, which can be found from Fig. 14, correspond well with the modal mineral composition measured in thin section. The sole exception is found in the melanocratic inclusion Wk. 65, which represents an inclusion in the hornblende-granodiorite, rich in hornblende and bearing quartz and plagioclase. Its peculiarly speckled and somewhat lighter hornblende differs from the other types in its optical properties. According to Fig. 14, this hornblende is poorer in iron but has the same Fo:Cs ratio as the chemically analysed hornblende Nh. 411. The fraction of hornblende Nh. 411 used for chemical analysis is magnetic; but, as the presence of magnetite inclusions could not be confirmed microscopically, it must be assumed that magnetite is a component of hornblende Nh. 411 in a very fine disseminated form. Apart from this special case (Wk. 65), which has not quite been clarified, the figure confirms that the analysed rocks are closely

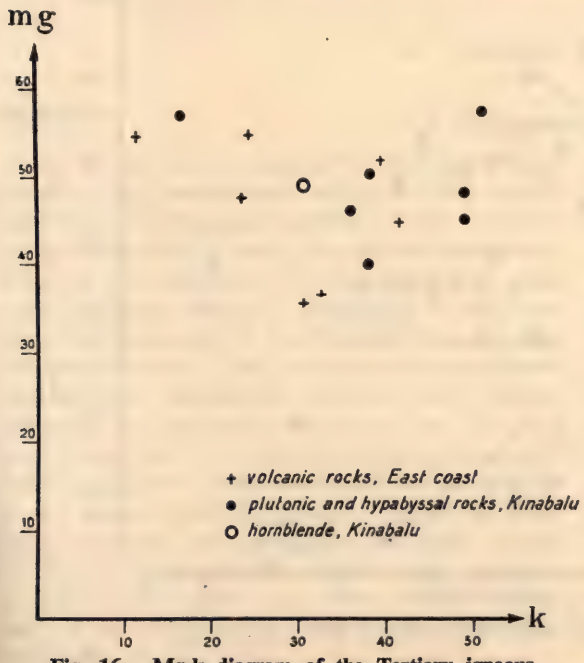


Fig. 16. Mg-k diagram of the Tertiary igneous rocks of North Borneo

$$mg = \frac{MgO}{MgO + FeO} \quad ; \quad k = \frac{K_2O}{K_2O + Na_2O}$$

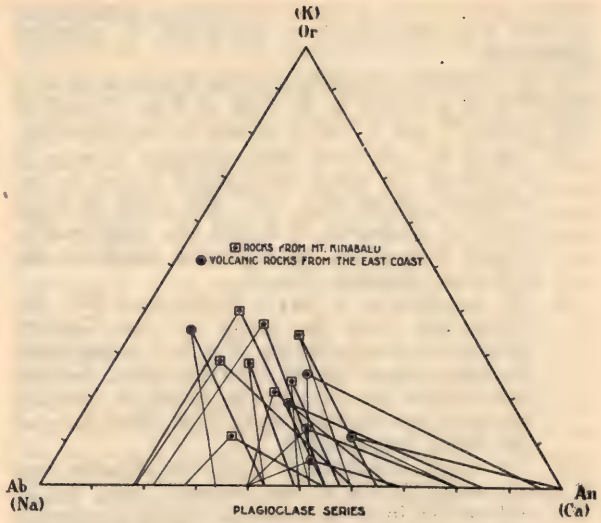


Fig. 17. Or-Ab-An diagram of the Tertiary igneous rocks of North Borneo

The projection points of the rocks are connected with their most calcic plagioclase by thick lines, with their most sodic plagioclase by thin lines. For volcanic rocks, only the plagioclase phenocrysts are entered in the diagram. Note the high potash content of the rocks from Mt. Kinabalu and the considerable anorthite content of the volcanic rocks from the east coast.

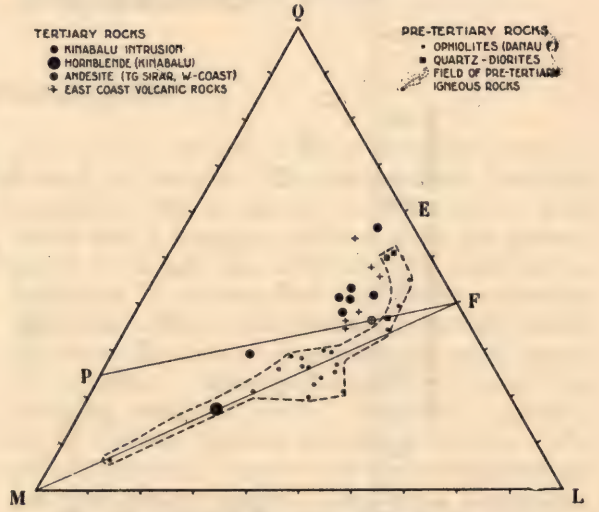


Fig. 18. Q-L-M diagram of Tertiary and pre-Tertiary igneous rocks of North Borneo

The point P represents the pyroxene compositions, F that of the feldspars, M the olivine and related compounds, L the nepheline and related compounds, Q pure silica and E the eutectic quartz/potash-soda feldspar. Rocks, whose projections are situated above the line PF are quartz-bearing, while those below this line do not contain normative quartz. Below the line MF feldspathoids are to be expected. Thus PF separates the rocks oversaturated with silica from those saturated, and MF the saturated from the undersaturated types.

related and are even, as far as the chemical composition of their dark constituents is concerned, in complete agreement.

If the chemical composition of the Kinabalu rocks is looked at as a whole, in the light of Figs. 15 and 16 and Tables IV and V, one is struck by the following:

1. The al, fm, c and alk values arranged in order of si content lie along well-defined curves in the variation, graph (Fig. 15). The slope of these curves is in respect of al and fm, considerably steeper than in the corresponding graph for the east coast volcanics (Fig. 9).
2. The isofalism al = fm (= 31) lies at si 209. By comparison with the graph for the Tertiary volcanics of North Borneo (Fig. 9), it is markedly displaced toward higher si (to the right). Similar relationships are also to be found in Tertiary extrusive and intrusive rocks from other parts of the Malay Archipelago.
3. The al-alk difference is quite considerable over the whole of the si-area covered; from this it follows that in all the rocks the anorthite molecule has played an essential part in the formation of feldspar. The findings mentioned under (2) and (3) suggest a Pacific association.
4. The k values for isofalic to slightly femic rocks are in part rather high (0·49, 0·51) and correspond to figures found in the potash series. We are therefore dealing with a rock-tribe of the calc-alkali series with a tendency toward the potash series.

Geologically, the most important result of the petrochemical examination consists in the demonstration that all the minor intrusions represented in Enclosure VI are consanguineous with the rocks of the Kinabalu massif proper. Since individual minor intrusions (e.g. the chemically analysed sample Nh. 422) break through Tertiary strata, this means that Mt. Kinabalu also represents a Tertiary intrusive body. Unfortunately, owing to lack of exact palaeontological data, the age of the Tertiary strata in the environs of Gg. Kinabalu cannot be determined precisely. Nevertheless, there are indications, as already mentioned on p. 51, which suggest that the Kinabalu intrusion is approximately of the same age as the volcanism on the east coast (late Te).

In the mg-k graph (Fig. 16) the Kinabalu intrusives and the volcanic rocks of the east coast together form a closed field. Nevertheless their variation graphs

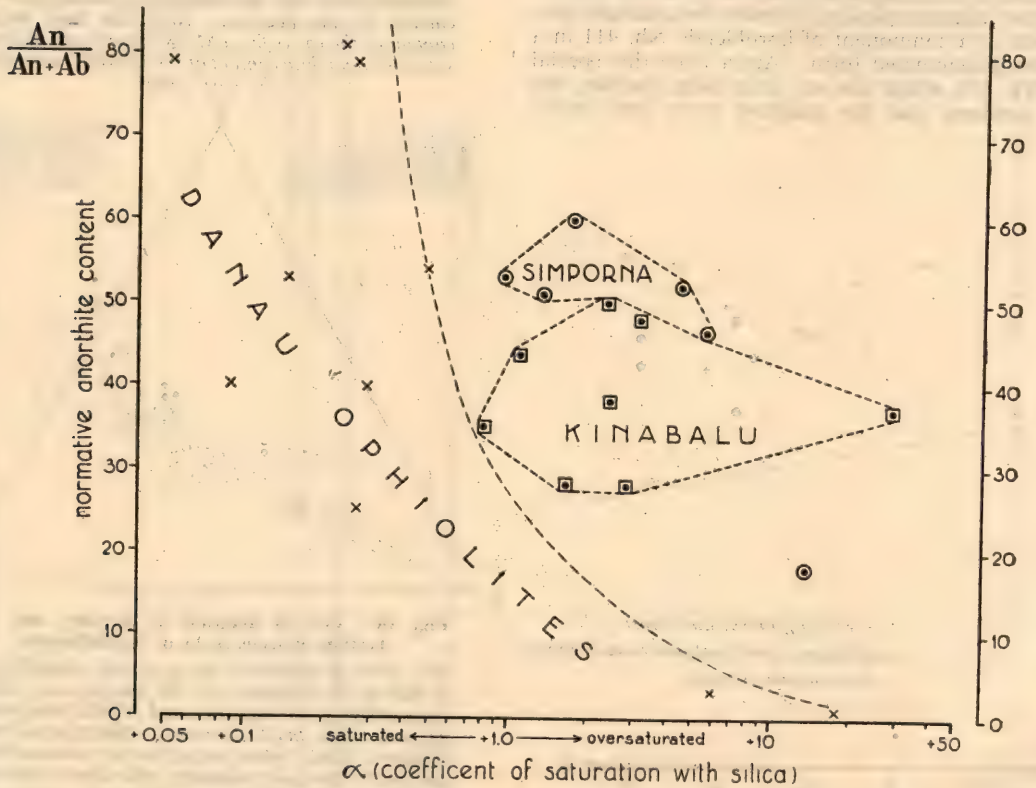


Fig. 19. Diagram showing relations between the normative anorthite content and the coefficient ∝ of saturation with silica in the Tertiary rocks from Simporna area, in Tertiary igneous rocks from Kinabulu area and in the ophiolitic rocks of the pre-Tertiary Danau Formation (except those undersaturated with silica, where ∝ is negative).

(Figs. 9 and 15), arranged in order of si content, are clearly differentiated. This is probably due not so much to considerable differences in the initial magmatic material as to the varying geological evolutions of the magmas. The highly explosive volcanism on the east coast was connected with crystallization, differentiation and assimilation processes other than those of the plutonic solidification on the west coast. The volcanic rocks are, almost throughout, richer in feldspar and anorthite content than the Kinabalu rocks (see Fig. 17). This is bound up with their higher alumina and lime content and also with the fact that, with the formation of pyroxene in place of hornblende, almost all the alumina present is used up in the formation of feldspar. From a comparison with other igneous rock series of the Malay Archipelago, it may be concluded that the course of variation of the volcanic rocks of North Borneo is of regional importance, while the development of the rocks of the Kinabalu intrusion has only a local character.

The Tertiary magmatic activity of North Borneo can be sharply distinguished from the ophiolitic magmatic manifestation of the preceding Mesozoic to Palaeocene. This is quite clear from the QLM triangle (Fig. 18). The Tertiary igneous rocks are *oversaturated* with silica (only two analysed rocks are merely *saturated* with silica); the Mesozoic magmatites, however, apart from special locally restricted cases, are either *undersaturated* or *saturated* with silica. Further evidence for this clear distinction is afforded by Fig. 19, which shows the relations between the normative anorthite content and Niggli's coefficient α of saturation with silica (Burri-Niggli, 1945, op. cit. p. 79). Owing to the logarithmic scale chosen for the abscissa (α) of this graph, the rocks undersaturated with silica (α negative) are not entered in the figure. After the Mesozoic to Paleocene ophiolitic magmatism of the Danau Formation of North Borneo, which produced mainly alkali-basaltic to sub-basaltic rocks, a highly Pacific volcanism followed in the Aquitanian to Lower Miocene epoch on the east coast, throwing up intermediary to acid lavas, ejectamenta and ashes; at approximately the same period, intrusions of acid isofalic magmas took place on the west coast.

CHAPTER VII

Pre-Tertiary Formations

A. DANAU FORMATION

Definition

One of the most remarkable, apparently syngenetic, rock associations which is very widely distributed in space and in time, is that of radiolarian cherts with a group of predominantly basic intrusive and effusive rocks, comprising a great many varieties, which is designated by the term ophiolite, especially in the literature on the Alps and the Apennines. The occurrence of radiolarites together with serpentines, diabases and spilites, frequently in the form of pillow-lavas, has long been recognized by various geologists. Pantanelli (1883) and Lotti (1886) attempted an explanation of this remarkable paragenesis. Later on Teall (1895) tackled the problem, followed shortly afterwards by Steinmann (1897), who returned in later works (1905 and 1926) to a discussion of the distribution and genesis of these formations.

Molengraaff (1900 and 1902) described a similar rock association in Central Borneo and designated it by the term *Danau Formation* because of its occurrence in the area of the great lakes (*danau* = " lake " in Malay). This term has been generally accepted in the geological literature on the East Indies and is therefore adhered to in the present report to denote an identical rock association. According to Molengraaff the group comprises radiolarian cherts as sedimentary guide rock besides clay-slates, sandstones, quartzites and small lenses of limestone. Among the eruptive rocks the following varieties occur: serpentine, gabbro, norite, diabase, diabase porphyrite, diabase tuffs and tuff breccias, together with some amphibolites and glaucophane schists. The Danau Formation strikes approximately E.–W. from West and Central Borneo to near the east coast. The area occupied by it has a length of 650 km.—according to more recent surveys (Zeijlmans, 1939) as much as 800 km. —and an average width of 60 km. (Molengraaff, 1914). It also occurs in the SE. part of Borneo and in other islands of the archipelago, including the Philippine Islands. The ophiolitic rocks collected by Molengraaff have not yet been examined on a basis of more recent knowledge.

The most comprehensive and most recent reports on petrographic examinations of ophiolites from the East Indies are those made by Roothaan (1925) and De Roever (1940).

The rock complex of the Danau Formation has also a wide distribution in North Borneo, where it consists of both sedimentary and eruptive rocks. The question arises as to how this formation can be separated from the others.

As regards the eruptive constituents there is, as a rule, no doubt as to what rocks are to be considered as belonging to the Danau ophiolites. The boundary between the Danau Formation and the more recent, granodioritic intrusives and the predominantly andesitic volcanic rocks does not, except in a few special cases, present any difficulties. Greater difficulties are encountered when determining the boundary between the Danau Formation and the older formations. In the Dent Peninsula, crystalline schists have a wide distribution. In general, the Danau ophiolites do not show traces of regional metamorphism. We are therefore of opinion that the gneisses, amphibolites and metamorphic slates and the associated quartz-dioritic rocks of the Dent Peninsula are older than the Danau Formation. However, similar metamorphic rocks occasionally occur closely associated with ophiolites, and it must be left an open question as to whether these are metamorphic varieties of Danau ophiolites or older crystalline schists.

By sediments of the Danau Formation we mean such sediments as were deposited during the period of the intrusion and extrusion of the ophiolites, which is unquestionably the case with the radiolarian cherts. The latter deposits are indeed very characteristic, but are as a rule restricted, and during the *mise en place* of the ophiolites flysch-like sandstones and shales were also deposited. The delimitation of these " Danau sediments " from the overlying and underlying beds is one of the most obscure and knotty problems in the geology of North Borneo. The outlines shown on the geological map must therefore be considered as very problematic and only provisional.

Occurrence of the Danau Formation

As regards extent, the rocks of the Danau Formation seem to rank next to the Tertiary formations, which occupy the largest area in North Borneo. The rocks of the Danau Formation extend from the SE. of the country to the NW. as a belt, which is widest in the SE. in the neighbourhood of Darvel Bay, gradually tapering toward the NW. The Danau Formation is cut into a south-easterly and a north-westerly part by a trough filled with Tertiary deposits which extends across the whole country in an approximately E.–W. direction along the Milian-Kinabatangan. Vast areas in each part are *terra incognita*, and more observations as regard the extension of the Danau Formation have still to be made. In the north of the country, in the peninsulas on both sides of Marudu Bay, and in the islands of Banggi, Manawali and Balambangan situated opposite Marudu Bay, there are, besides small scattered outcrops, some more extensive and coherent proven series of the Danau Formation. Of the remaining isolated Danau outcrops shown on the geological map, that of Tg. Batu Larei Larei, NW. of Sandakan (NE. coast of North Borneo) has been proven by rock samples (spilites); of the outcrops 30 km. ESE. of Jesselton and 15 km. WSW. of Pinanga (in the interior) there are no samples, except one of a limy sandstone which is not typical of a Danau sediment and might be of Tertiary age. According to reports by Niethammer, these two isolated occurrences are strongly squeezed clay-slates with sandstone intercalations, and in his view it is very problematic whether they belong to the Danau Formation.

THE ROCKS OF THE DANAU FORMATION

The Sedimentary Rocks

Shales and Flysch-like Sandstones

The guide rocks of the Danau Formation, ophiolites and radiolarian cherts, occur in a series of sediments which consists of alternating layers of more or less sandy shales and sandstones. Various tints of grey predominate, but brown and red, green, white and variegated colours also occur. Lithologically there is no essential difference between them and the rocks of the Tertiary Formation, but the rocks of the Danau Formation are much more strongly folded, contorted and imbricated. Hotz and Niethammer, who examined the NW. section of the Danau Formation, have, in view of this conspicuous property, referred to them in their reports and maps as " squeezed strata ". They comment that there is no sharp line of demarcation between them and the more recent (Tertiary) sandstones and shales. Both authors draw attention to their close resemblance to Alpine flysch; Stamm and Reinhard

have also noticed this similarity. Because of the intense folding and distortion of the squeezed strata Hotz and Niethammer considered them to be older than Tertiary, and assumed a Cretaceous age. Since no fossils have been found so far—except in one case which will be dealt with later—their age remains problematic. Similar rocks occur in the SE. sector of the Danau Formation. They are referred to by Wanner (1921) as Darvel Bay strata.

Thin sections were prepared of 14 rock samples. Some of the sandstones examined contain a limy, but most of them a siliceous-argillaceous, cement. Various samples contain, besides quartz grains which predominate, feldspars with frequent occurrences of chequered albite. Special mention must be made of the rounded fragments of radiolarian cherts found in several of the samples examined. Consequently, the squeezed strata are, at any rate in part, more recent than the radiolarites. In thin section they do not differ from the sandstones, the Tertiary age of which has been proven by fossils. This fact is mentioned merely for the sake of completeness, and not to serve as a basis for drawing unjustified conclusions as regards the age of the squeezed strata.

Remains of foraminifera were identified in a thin section of a quartzitic sandstone (sample Nh. 193, 6 km. ENE. from Kota Belud, NW. coast). The limy tests show distinct corrosion; for the greater part they have been dissolved in minute particles of calcite floating in quartz grains, without having changed their original position. A *lepidocyclina* (see Figs. 3 and 4 of Plate I) can be recognized among these largely silicified fossil remains. Prof. M. Reichel, who was shown the thin section, expressed his opinion that it was most probably a form of the *L. sumatrensis* Brady group, namely, the *minor* Rutten variety. This would indicate that among the sediments shown on the map as Danau Formation there are some of Tertiary, namely, of Upper Oligocene-Miocene age. Specimens of *lepidocyclina*, though badly preserved, were also found in two other thin sections from the same sample.

Radiolarian Cherts

Radiolarian cherts are found throughout the squeezed strata in the form of intercalations. As is the case with the rocks bearing them, these intercalations show traces of having been exposed to extreme tectonic forces and they are often reduced to a crush-breccia. The thickness of the beds and lenticles is at most some 10 metres, but generally less. The radiolarian cherts are sometimes the sole key rocks in the Danau Formation, but as a rule they are accompanied by ophiolites. The rocks in question are mostly compact, fracture conchoidally and have a resinous, or more rarely a dull appearance. Feebly porous varieties of earthy appearance do not occur so frequently. The predominant colours are brown to red, but yellow, green, white and occasionally variegated hues also occur. The radiolarites often contain a network of milky-white veins of quartz, chalcedony and calcite, occasionally accompanied by barytes. This network is sometimes so dense that the radiolarites are broken up into lumps, which are suspended in the veins of quartz, chalcedony and calcite. Structures are then formed which are typical of ring or cockscomb ores.

The examination of 26 thin sections showed that the rocks are often speckled throughout with radiolaria. Unfortunately, the latter were so badly preserved that the plan to submit the material to an expert for determination* had to be dropped, a circumstance the less to be regretted because even well-preserved radiolaria are unsuitable for age determination. The groundmass in which the radiolaria are embedded is a crypto-crystalline mixture of silica and iron oxide, probably precipitated from a colloidal solution.

In general, the more the ground-mass is pigmented by iron oxide the more easily radiolaria are visible. Figs. 1 and 2 of Plate VI represent such a case. Fig. 1 is a picture taken without analyser. The rock is full of specks of radiolaria; the flaws are filled with calcite and quartz. Fig. 2 shows the same section between crossed nicols. The radiolaria are somewhat vaguer, but still clearly recognizable. It can be seen that they are filled with specks of chalcedony. Figs. 3 and 4 of Plate VI give a picture of a somewhat less and unevenly pigmented radiolarian chert. Fig. 3 was again taken without analyser, and the radiolaria still appear contrasted with the pigmented groundmass. A quartz vein can be seen near the upper edge of the picture. Fig. 4 represents the same section between crossed nicols. All traces of the radiolaria have disappeared as the rock is entirely recrystallized. Recrystallization phenomena, often combined with metasomatic replacements, are not confined to radiolarites. On the contrary, these processes act very generally and have not only converted the rocks accompanying the ophiolites but also the ophiolites themselves. This phenomenon will, therefore, be dealt with in a separate chapter.

Limestones and Marls

Together with the radiolarian cherts there are isolated occurrences of limestones and marls—probably particularly in the overlying beds—now and then interstratified with the radiolarian cherts or replacing them laterally (observation by Irving at Pulau Batawan on the E. coast of the isle of Banggi, northern extremity of Borneo). Most of these limestones and marls are brownish-red, like the radiolarites; sometimes they are greenish or white, or occasionally flamed white and red. They often show a network of white calcite veins and then look very much like the white-veined radiolarian cherts. These carbonate rocks are much less common than the radiolarites. Hotz collected them in the islands opposite the northern extremity of Borneo, in Pulau Burong, north of the Klias Peninsula, west coast (cf. cross-section Fig. 20) and at the abandoned manganese mine of S.Taritipan (cf. Enclosure V and cross-section 1 of Fig. 3). Niethammer collected various samples from the Kudat Peninsula and from the interior, south of Mt. Kinabalu. Limestones of this kind seem to be very rare in the SE. part of the country, in spite of the frequent occurrence of the Danau Formation. Stamm found them in the Tingkayu, and a sample of black limestone is known from the Segama.

Thin sections of the 30 limestone and marl specimens under consideration were prepared in a search for

*The radiolaria from the radiolarites collected by Molengraaff in Netherlands Central Borneo were thoroughly examined by G. J. Hinde. A full description is given in Molengraaff (1900 and 1902), Appendix I.

traces of possible micro-fossil content. Approximately one-third of the specimens actually proved to be fossiliferous. The micropalaeontological investigation was carried out by Prof. M. Reichel, with the results shown in Appendix III. We shall return to them again in the section on the tectonics and age of the Danau Formation. Here follow just a few remarks on the microscopic constitution of the limestones and marls.

Those rocks not recrystallized exhibit a cryptocrystalline texture. The calcareous rocks are also, like the radiolarites, more or less strongly pigmented with iron oxide, and so the rock is often brownish-red in colour. One has the impression that one is dealing

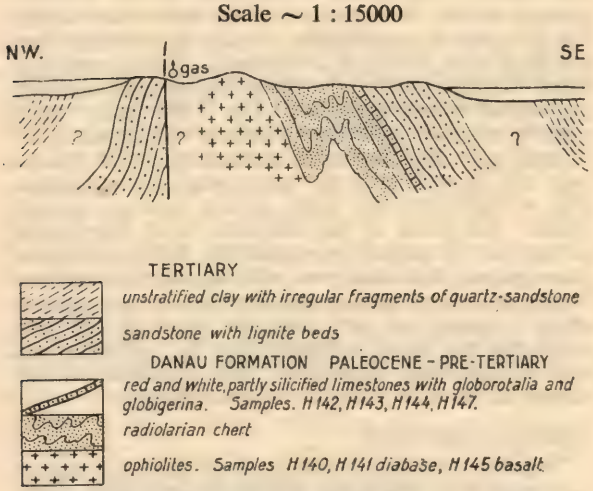

Scale ~ 1 : 15000
NW.
gas
SE
?
?
?
TERTIARY
unstratified clay with irregular fragments of quartz-sandstone
sandstone with lignite beds
DANAU FORMATION PALEOCENE - PRE-TERTIARY
red and white, partly silicified limestones with globorotalia and globigerina. Samples. H 142, H 143, H 144, H 147.
radiolarian chert
ophiolites. Samples H 140, H 141 diabase, H 145 basalt

Fig. 20. Section through P. Burong N. of Klias Peninsula after W. Hotz.

with inorganic precipitate rocks, as in the case of the " groundmass " of the radiolarian cherts. More than half of the rock samples show no trace of organisms; in others, micro-fossils are concentrated in bands or nests (Plate VII, Fig. 1). Here the micro-fossils are also embedded in a compact " groundmass ", as are the radiolaria in the radiolarites.

In one rock (H. 75) numerous calcified radiolaria and angular fragments of radiolarian chert lie in a finely-crystallized calcite groundmass. The cherts are corroded at the edges and evidently represent residues not yet converted into carbonate. Incipient silicification can be distinguished in other samples. As already mentioned in the section on radiolarian cherts, signs of recrystallization and metasomatic replacement are also widespread among the Danau limestones. This will be dealt with in a later chapter.

The Ophiolites

Igneous rocks which, as already mentioned, we designate as ophiolites in accordance with the nomenclature adopted for identical rock associations, appear everywhere in the Danau Formation, associated particularly frequently with radiolarian cherts. In North Borneo, as elsewhere, this rock group includes a large number of different kinds of rock connected with each other by transition members. They occur in the sediments of the Danau Formation, with which they have been folded and imbricated and often kneaded to coarse tectonic breccias. They are found usually as intercalations of small thickness, about 10 m., or as stocks about 100 m. in diameter. As a rule several types of rock are represented in individual ophiolite occurrences, an exception being serpentine, which appears occasionally in more or less uniform lenticles and stocks. The multiformity is so great that neither the detailed sketch-maps nor the cross-sections can do them justice, not only on account of the inadequate scale employed, but also because the ophiolitic areas naturally received only cursory consideration from the geologists who worked in the service of oil companies. We shall therefore confine ourselves to describing the rock samples collected, and touch upon such pressing problems as that of the history and the origin of the Danau Formation or that of its age only in order to stress the problematic element in our subject, not in order to give answers to these questions. Moreover, a land such as North Borneo, with its impenetrable virgin forest, would hardly be found suitable for such an investigation.

The diversity of the ophiolitic rocks is primarily conditioned by the wide range of variation in their chemical constitution—their SiO_2 content varies between 36% and 69%—and by the development of different types of texture in which all gradations are represented, from holocrystalline coarse-grained to highly-vitreous microlithic. Besides the chemical composition the rate of cooling is responsible for the great variety of rocks, and this again will have been determined by the form and size of the intrusive and extrusive bodies.

As a result of strong imbrication, however, the original form of the ophiolite bodies can no longer be ascertained; the division in the following pages into intrusive and extrusive rocks is made exclusively on the basis of texture. Within each group the basic rocks, being the typical and commonest representatives of the ophiolites, will be described first, followed by the more acid members. It will be found that this order probably corresponds to the differentiation sequence.

Intrusive Rocks of the Ophiolite Series

SERPENTINES, PERIDOTITES AND PYROXENITES

Rocks containing less than 25% plagioclase or its alteration products, principally saussurite, fall into this category, represented by 90 samples, of which 70 were examined in thin section. Between the serpentines and the peridotites there is a continuous transition series. Transitional types occur also between these two rock groups and the troctolites.

SERPENTINE AND RELATED ROCKS

Among the ophiolitic rocks the serpentines are certainly the commonest and most generally distributed. The number of rock samples available is correspondingly large (over 60, of which 37 were examined in thin sections). As a rule the serpentines occur together with various other ophiolitic rocks. Locally they form larger and more uniform bodies in which streaks of peridotite and olivine-gabbro may occur. Such an occurrence is to be found, for instance, in the Paninsau, in the upper Blantian Valley (cf. Enclosure X). These extensive serpentine bodies are distinguished by their rugged outlines and the scanty brushwood upon them. They are easy to recognize on aerial photographs.

Massive, schistose and brecciated forms are about equally common. Serpentine-breccia is often traversed by ore-impregnated slickensides (magnetite). Slickensides with glassy-looking gliding planes are common. Colour varies through grey-green, yellowish-green and dark-green to black. The rocks are often "flamed" light and dark green, or are mottled in different colours.

Dunite-serpentines with lattice and mesh structures

As examination of the thin sections shows, lattice and mesh structures are about equally represented among the dunite-serpentines. Fig. 4, Plate IX, and Fig. 1, Plate X, illustrate such kinds of textures. Fig. 3, Plate IX, shows a serpentine-mylonite. The serpentine is slightly yellowish-green, though occasionally colourless, in thin section, with streaks of isotropic material. It is usually dusted with ore. As accessories occur: bastite plates, saussurite nests, chlorite, talc, brucite, golden-yellow mica, chromite and calcite in proliferations and in filiform cracks. When bastite predominates the dunite serpentines merge into:

Bastite-bearing Serpentines (*Harzburgite Serpentine*)

The schillerized cleavage planes of the greyish-green or yellowish-green bastite plates in the section are easily visible to the naked eye. In thin section they are of greyish-green or yellowish-green colour. Occasionally some remnants of olivine and diallage grains may be seen.

The *saussurite-serpentines* are dark-green rocks in which the bluish-white saussurite occupies small interstices and gives the rock its characteristic mottled appearance. In thin section the saussurite appears as a muddy brown, nearly isotropic mass with aggregate polarization. It is an exception for plagioclase residues to be present; the cleavage of the original plagioclase is often preserved in the saussurite. When saussurite or plagioclase predominates, troctolites may develop from the harzburgite serpentines. In Fig. 1, Plate X, the thin section of a saussurite-bastite serpentine is shown, though bastite is not present in the portion represented.

Two more accessory constituents, talc and chlorite, may predominate so strongly as to become essential or even exclusive constituents. In such a manner massive *talc and chlorite rocks* may comprise streaks in the serpentine. The following rocks appear to occur also as intercalations in the serpentine.

Nephrite and Jadeitite

Wanner (1921, p. 164) refers to an outcrop of nephrite discovered by Stamm in the middle course of the Segama (marked W. 9 on Enclosure VIII), 8 km. down-stream from Kuala Bole measured as the crow flies. No sample of this, however, was available, nor was nephrite present among the material of Stamm's examined by us, while a sample (St. 193) from the same locality is of completely slicken-sided, foliated serpentine. Nevertheless, we do not doubt the accuracy of Stamm's observation.

From a loose block in the immediate vicinity of the quartzitic sandstone with lepidocyclina residues (about 6 km. ENE. of Kota Belud, NW. coast, described on p. 65) Niethammer collected several samples (Nh. 192) of grey-green, compact aphanitic nephrite, translucent at the edges and with a white crust due to weathering.

As the thin section shows (see Fig. 2, Plate X), the rock consists of a finely nematoblastic felt of colourless actinolite filaments too minute for optical determination. The refractive index is about 1·616. Yellowish-green, isotropic, strongly refractive grains occur in small stringers and nests (spinel? garnet?).

This occurrence is in the form of an isolated block, the rock *in situ* being in consequence unknown; but five other rock samples from the eastern slope of Mt. Kinabalu were collected by Niethammer in the River Makadau, a head-water tributary of the River Sugut, approximately 12 km. WNW. of Paranchangan. This occurrence is particularly worth attention because the Danau ophiolites are riddled here by microgranodiorite veins. In addition to the rocks described below, samples of serpentine, dunite and radiolarian cherts come from the same locality.

One sample (Nh. 499) shows a streak of light grey-green nephrite in black serpentine. In thin section the serpentine exhibits a finely nematoblastic texture, with ore-dust distributed in streaks, and isolated chromite and magnetite grains. The tiny actinolite needles of the nephrite felt, whose hue ranges from colourless to light green, are even more minute than the antigorite needles. The arrangement of the hornblende needles is markedly parallel.

Another sample (Nh. 454) consists half of black serpentine and half of a light-greenish-grey, conchoidally fracturing rock of considerable hardness (6–7) and of specific gravity 3·26. It can be melted fairly easily by the blow-pipe to a hard glass, and gives an intense Na flame. These findings are applicable to jadeitite. In thin section the rock is found to consist of extremely fine flakes, strongly impregnated with titanite dust. In so far as its optical properties can be ascertained, it appears to be a biaxial mineral with a small, positive axial angle.

A very similar rock (Nh. 460) with calcite in fine cracks, exhibits under the microscope a strongly cataclastic texture. Porphyroclasts of jadeitite-diopside, optically definable as such, float in the form of a fine plexus of the same mineral.

Finally, a light greenish-grey, massive *zoisitite* (Nh. 453) and a yellowish-green to dark-green *clinozoisite-epidote rock* (Nh. 485) come from the same locality. Both are microcrystalline, monomineral rocks.

Niethammer makes no mention of their relationship to other rocks from the same locality.

PERIDOTITES

Dunites

These are rocks ranging in texture from aphanatic to fine-grained, greenish-black to pitch-black in colour when the olivine is subordinate to the serpentine, and grey to greenish-grey when olivine predominates. In the latter case the rock generally shows an ochreous crust, the result of weathering, and, in thin section, strong cataclase. The olivine is very rich in magnesium; +2V varies around 90°. Both olivine and serpentine are usually sprinkled with ore. Talc, chlorite, actinolite, chromite and occasionally calcite in fine cracks, occur as accessory constituents. In Fig. 1, Plate IX, a dunite with olivine fragments is shown, embedded between antigorite lamellae. Fig. 2, Plate IX, shows the thin section of a saussurite-bearing dunite. The olivine-serpentine intergrowth shows a distinct mesh structure. The saussurite, visible in the illustration as black, rounded or hollowed pockets and pipes, forms a limpid mass with the finest aggregate polarization. The cleavage lines and twinning lamellae of the original plagioclase are easily recognizable. Saussurite sometimes forms a brownish isotropic mass with occasionally weakly abnormal polarization and proliferations of muddy brown prehnite. The rock was analysed and yielded the following values.

R. 44. Dunite with saussurite pockets, Blantian River, from a loose block:

SiO_2	36·34
TiO_2	Tr.
Al_2O_3	6·18
Fe_2O_3	2·89
FeO	5·80
MnO	0·04
MgO	32·86
CaO	4·40
Na_2O	0·34
K_2O	0·05
H_2O-	0·19
H_2O+	11·08
P_2O_5	Tr.
Cl	0·14
Total	100·31

Specific Gravity: 2·76
Analyst: P. Esenwein

The mode showed the following values: serpentine 71%, olivine 9%, saussurite 19%, ore 1%.

Among the accessory constituents mentioned, actinolite may occasionally be an essential one. In such actinolite peridotites green spinel may also occur in addition to chromite. Orthorhombic pyroxene and diallage may also be present and become primary constituents. The dunites are therefore connected by transition types with lherzolite and harzburgite.

Lherzolite and Harzburgite

The diallage is generally fresh; the orthorhombic pyroxene frequently replaced by bastite; the olivine strongly permeated with serpentine. The rocks are always rich in olivine, while the pyroxenes range between 20 and at the most 40 volume %. Orthorhombic pyroxene and diallage occasionally show parallel intergrowth. The lherzolites seem to occur more frequently than the harzburgites. Saussurite occurs sporadically in interstices. Hornblende, colourless or of a very pale brown, occasionally appears. It is usually associated with diallage, with which it may form delicate myrmekite-like intergrowths, in one case also with green spinel. Garnet with kelyphitic border was seen in one sample only.

PYROXENITES

Whereas the peridotitic rocks are distributed among various occurrences of ophiolite, predominantly pyroxene-bearing rocks rarely seem to occur. A sample of light greyish-green, medium- to small-grained, serpentine-bearing *pyroxenite* (L. 195) was collected by Leicester on the SE. coast, 15 km. SW. of Lahad Datu. The rock appears in thin section to be strongly cataclastic. Diopside porphyroclasts up to 3 mm. in size lie in finely pulverized diopside. The rock is penetrated by streaks of mylonite, with serpentine as filling mass.

The Hotz collection contains three samples (H. 26, 32, 33) of *bronzitite* originating from the island of Manawali off the northern tip of Borneo, where they occur in conjunction with peridotites, serpentine and radiolarite. Two of them are coarse-grained, spathic rocks, brownish-grey to greenish-grey in colour, and having bronzite crystals up to 3 cm. in size. The big grains of orthorhombic pyroxene (2V ~ 90°) are surrounded by a narrow border of colourless, reed-like hornblende. The same hornblende occurs also in pockets, as a tangled tissue in which colourless chlorite and talc are present. A third specimen shows a small-grained texture; the rock is mottled dark grey and black. Orthorhombic pyroxene forms the major constituent here as well; the grains are between 0·5 mm. and 2 mm. in size. Maximal double refraction $n_\gamma - n_\alpha = 0{\cdot}013$. Pleochroism n_γ greenish, n_α reddish, hardly noticeable, 2V ~ 90°. The grains are thinly dusted with ore and bordered with ore-dust. A most delicate pilite felt, heavily powdered with ore, occurs in pockets. A little olivine in interstices; rarely plagioclase; diallage quite sporadically.

GABBROS

Judging from the great number of rock samples available (60), gabbroid rocks are almost as frequently represented as serpentines among the intrusive ophiolites. Like these, the gabbros also occur occasionally in stocks, but are more frequently found in the form of blocks and lenses of widely differing size, together with other ophiolites. Thin sections of nearly all the gabbroid rocks were available.

Olivine is very frequently associated with the two major constituents of gabbros, viz. basic plagioclase and diallage, but an orthorhombic pyroxene is associated with them only in a few cases. The proportions of the constituents mentioned can vary very widely; the diallage may be uralitized, the plagioclase saussuritized or albitized and various textures are exhibited. The rock may be uniformly granular, or

may very often exhibit streaked and also, in the event of strong cataclase or protoclase, gneissose structure. Consequently a very wide range of variation is to be found in the gabbroid rocks. and several types are distinguished which, however, merge into one another without clear-cut boundaries.

THE TWINNING LAWS OF THE PLAGIOCLASES OF GABBROID ROCKS

The determination of the anorthite content and the twinning laws of the plagioclases was carried out, as far as the state of preservation permitted, on the Fedoroff universal-stage by Dr. O. Grütter. The An content will be given when each individual type of rock is considered. The twinning law distribution, however, is set out in condensed form in table VII, p. 70. The number of twinning laws determined is certainly not large enough to enable any rule for their distribution among different gabbro-types to be deduced from the table. It is nevertheless remarkable that the presence of Carlsbad twins is confirmed much more often in the case of the olivine-bearing gabbros than in the case of types free from olivine. On the other hand, acline and Ala twinning occur relatively frequently in the albite gabbros, while Carlsbad twinning occurs seldom.

CHEMICAL ANALYSES OF GABBROS

Four different types of gabbros were subjected to chemical analysis. The investigation yielded the following results.

	R. 38	R. 22	R. 24	J. 202
SiO_2	41·46	46·17	46·33	45·31
TiO_2	0·14	0·13	0·32	3·16
Al_2O_3	16·29	27·16	22·60	16·53
Fe_2O_3	4·74	1·64	1·03	8·33
FeO	3·37	0·88	3·18	6·26
MnO	0·12	0·01	0·06	0·11
MgO	16·97	4·55	10·16	5·44
CaO	9·35	15·24	12·84	8·96
Na_2O	1·19	1·92	1·40	2·97
K_2O	0·00	0·03	0·52	0·48
H_2O-	0·49	0·16	0·13	0·16
H_2O+	6·33	2·43	1·37	2·71
P_2O_5	0·05	0·23	tr.	tr.
CO_2	0·00	—	—	—
Cr_2O_3	0·06	—	—	—
S	0·15	—	—	—
Cl	0·00	—	tr.	tr.
Total	100·71	100·55	99·94	100·42
Deduction for S	0·07			
	100·64			
Sp. Gr.	2·75	2·76	2·90	2·89

R. 38: *Troctolite.* Blantian River. Medium-grained (2–5 mm.). Plagioclase (79% to 85% An), fresh, strongly serpentinized olivine with magnetite dust, little yellowish-brown bowlingite. *Mode:* plagioclase 45%, olivine 13%, serpentine 33%, bowlingite+ore 9%. *Analyst:* H. Preiswerk.

R. 22: *Olivine gabbro.* Blantian River. Medium-grained (2–4 mm.), weakly gneissose-fluidal. Plagioclase (78% to 87% An), very fresh, diallage likewise, brownish, olivine altered for the most part into greenish bowlingite, under ore-dust deposit. *Mode:* plagioclase 74%, diallage 9%, olivine+bowlingite 15%, ore 2%. *Analyst:* H. Preiswerk.

R. 24: *Olivine gabbro,* uralitic, Blantian River, medium-grained, massive. Plagioclase fresh (70% to 88% An). Diallage, bordered and interpenetrated by very faintly green hornblende, often almost completely altered into a tangled, diablastic texture of reed-like hornblende. Olivine fresh, also bordered by almost colourless hornblende under ore-dust deposit. Sporadically little nests of light-brown biotite flakes, a grain of orthorhombic pyroxene, little green spinel. *Mode:* plagioclase 70%, diallage +uralite 16%, olivine 12%, accessories 2%. *Analyst:* P. Esenwein.

J. 202: *Uralite gabbro,* incipient albitization (gabbro-diorite). Subahan River, Lahad Datu. Medium-grained (1–5 mm.) massive. Plagioclase 20 %–54% An), rather fresh, frequent zonal mottling,

turbid brown in parts and then with inclusions of prehnite, more rarely zoisite and zeolites. Relics of diallage still present, mainly altered into bluish-green uralite and chlorite of the same colour. Rich in ilmenite, little apatite. *Mode:* plagioclase 70%, diallage + uralite 23%, ore and apatite 7%. *Analyst:* P. Esenwein.

As may be seen from the modal constitution of the minerals, the rocks concerned, apart from the troctolite R. 38, are highly leucocratic. As in each case one thin section only was analysed, the results of integration cannot yield a true picture of the modal composition of such relatively coarse-grained rocks. In actual fact, the appearance of the hand samples would rather lead one to assume them to be mesocratic rocks.

DESCRIPTION OF ROCK TYPES

Troctolites

Judging by the available samples, these rocks seem to be confined to few occurrences, although represented by different types.

Reinhard collected a large number of samples in the Blantian River in the south-east of the country, near the frontier of Dutch Borneo; from Wenk come some samples from the S.Malog, a right-bank tributary of the S.Kuamut, itself the largest right-bank tributary of the Kinabatangan. A medium-grained massive rock, mottled light-grey to black, with a proportion of plagioclase to olivine of 1:1, may be taken as the normal type. More frequently met with than such uniformly-grained massive rocks are the strongly streaked troctolites, in which plagioclase and olivine are concentrated separately in bands. In these rocks the grain size is not uniform and areas with small grains (1 mm.) alternate with nests of coarse grains (10 mm.). The predominance of olivine, or of its substitute serpentine (mela-troctolite), causes types transitional to plagioclase-bearing dunites to appear; the gradual disappearance of olivine causes troctolites to pass over into leuco-gabbros and anorthosite. Dunitic and anorthositic streaks are often present in the same sample.

The olivine-rich rocks (troctolites and olivine gabbros) show characteristic weathering forms, as the olivine is often decomposed, giving an earthy-yellow coloured product which is easily removed, whereby a pitted surface arises. The olivine rocks tend to form pisolitic limonite and laterite.

The diversity of types of troctolite, conditioned by different mineral content and texture, is accentuated by differences noticeable only in thin section. Other constituents, besides olivine and plagioclase, can occur. Diallage is particularly prominent; orthorhombic pyroxene seldom appears. Both readily form narrow borders around grains of olivine where these are in contact with, or fill interstices between, grains of plagioclase.

The anorthite content of the plagioclase, determined on the Fedoroff universal-stage, varies between 70% and 90%, and rises exceptionally to 100%. Limits of variation in the individual section are somewhat narrower. Zonal texture is only faintly developed; reverse zoning in one case was found. The anorthite content of the various twinning lamellae is often different; the difference can amount to 15%. The plagioclase is invariably penetrated by innumerable, very fine cracks which extend radially from more or less serpentinized olivine grains (Fig. 3, Plate VIII). These cracks are filled with a brown, earthy substance; prehnite is also occasionally found in them. Large plates of plagioclase often harbour several grains of olivine, in which case the texture is typically poikilitic.

The plagioclase is occasionally, and the olivine always, partly or wholly replaced by secondary mineral aggregates. We are probably dealing here with products

TABLE VII. FREQUENCY DISTRIBUTION OF THE PLAGIOCLASE TWINS IN THE GABBROS

Twin Law	albite-gabbro		olivine-free gabbro		olivine-gabbro		all gabbros	
	Number of det. Twins	%	Number of det. Twins	%	Number of det. Twins	%	Number of det. Twins	%
Albite	22	45	42	43	79	39	143	41
Carlsbad	2	4	10	10	39	19	51	15
Complex albite-Carlsbad	1	2	14	14	26	13	41	12
Pericline	9	18	20	20	43	21	72	21
Acline	9	18	8	8	4	2	21	5
Ala	5	15	1	1	4	2	10	3
Complex albite-Ala ..	—	—	—	—	1	—	1	—
Manebach	1	1	1	1	5	2	7	2
Baveno	—	—	1	1	2	1	3	1
Total of det. Twins ..	49		97		203		349	

formed by hydrothermal solutions following consolidation.

The saussuritization of the plagioclase begins with a brownish turbidity, especially at the edges, where plagioclase grains border on olivine. In the advanced stage the plagioclase is completely altered into a brownish, occasionally colourless, isotropic or faintly aggregate-polarizing mass, in which proliferations of prehnite, zeolites and, occasionally, colourless hornblende, may occur.

The olivine is always more or less altered into colourless or faintly yellow, greenish to bluish serpentine, usually dusted with ore. Decomposition products of the bowlingite type occasionally accompany it.

Some samples exhibit strong cataclasis, and this has given a grey-violet tint to the plagioclase.

Greater abundance of diallage causes the troctolites to merge into olivine gabbro.

Olivine Gabbro

The area of distribution is somewhat greater than that of the troctolites. They occur together with the latter in the Blantian River, the locality from which most of the samples come (cf. Enclosure X). Rock samples were also collected from the Imbok and Malog rivers, both right-bank tributaries of the Kuamut, and from the abandoned copper mine at the head-waters of the Karamuak, a large left-bank tributary of the Milian (Kinabatangan) (cf. Enclosure VII).

Medium-grained, grey and black speckled, massive types predominate over faintly gneissose or streaked varieties. The grain becomes finer under stronger cataclasis and the plagioclase assumes a grey-violet hue as in the case of the troctolites.

Granular-gabbroic texture predominates, ophitic texture occurs seldom, sub-ophitic and poikilitic more often. Figs. 1–4, Plate VIII, illustrate the texture of olivine gabbro. The upper two figures show a portion poor in olivine, sub-ophitic in texture. The lower figures show a portion rich in olivine, with sub-ophitic and poikilitic areas.

The An content of the plagioclases varies between the same limits, as in the case of the troctolites between 70% and 90%. Weak, normal zonal structure is occasionally to be seen, strong, reverse zoning in two cases (core 70%, rim 90% An). The plagioclase is, almost without exception, quite fresh, with fine flaws radiating outwards from included, more or less serpentinized, olivine grains, on which prehnite or an isotropic, brown, earthy mass is often deposited. The plagioclase occasionally exhibits a brownish, cloudy reaction rim, around included, somewhat serpentinized, olivine grains. This rim seems to be produced by minute, extremely fine hornblende needles.

The olivine is always more or less altered to a yellowish-greenish-bluish tissue of serpentine-bowlingite, together with deposition of ore-dust.

The diallage appears in brownish plates ophitically speckled throughout with plagioclase, occasionally turbid brown at the edges, and in narrow borders around olivine grains embedded in plagioclase. Orthorhombic pyroxene or brown hornblende is occasionally to be found as a narrow rim round diallage tablets. Only isolated pockets of felted colourless hornblende, scanty chlorite or light-brown biotite, were detected, with one occurrence of green spinel as an accessory constituent.

Despite the wide distribution of the gabbroid rocks, the material collected does not include a single representative of a typical gabbro, i.e. of a diallage-plagioclase rock. Either the diallage is more or less replaced by uralitic hornblende, or the plagioclase is saussuritized; still more often, both saussurite and uralite are present at the same time. In addition, another peculiarity begins to show itself—a peculiarity which becomes the rule among certain effusive rocks of the ophiolite clan, namely, the albitization of the plagioclases.

Uralite and Saussurite Gabbro

These are usually medium-grained rocks, massive or ranging from gneissose to streaked. A divergently radiating disposition of the plagioclase laths, and ophitic texture, are often conspicuously noticeable even to the naked eye. Their principal area of distribution appears to lie in the SE. of the country. Most of the samples originate from the Blantian and from the Subahan and Diwata, two small rivers flowing into Darvel Bay, but these gabbro types also occur in the Segama and on the SE. slope of Kinabalu.

The original granular or ophitic texture is often still preserved. With strong uralitization coarsely fibrous textures predominate.

The anorthite content of the plagioclases in this rock group fluctuates between wider limits, from 50% to 97%. At the commencement of albitization, outer zones richer in albite begin to form whose An content may fall to 20%. Normal zone structure (calcic core, more sodic outer shell) is very common. The plagioclase is seldom quite fresh. The alteration begins with a brownish turbidity out of which, under stronger " saussuritization ", prehnite and colourless hornblende in particular develop, and more rarely zoisite and zeolites.

Relics are present of diallage which, for the rest, has been altered into a reed-like aggregate of colourless or faintly bluish-green uralite in which chlorite of the same colour may also be found. Where such uralite pockets border on, and grow into, plagioclase, they are intensely blue-green in colour. Brown hornblende, penetrating or forming a rim round the diallage, and orthorhombic pyroxene occur sporadically. The orthorhombic pyroxene is almost always intermingled with bastite. Olivine appears less often and then only in a few grains. The presence of quartz, presumably a secondary product, was established only once. Ilmenite, titanite and apatite occur as accessory constituents.

The colour index is subject to great variation. Next to rocks in which diallage and plagioclase—or their alteration products—more or less maintain a balance, occur melanocratic types as well as leuco-gabbro; neither, admittedly, in coherent rock bodies but as streaks.

We have spoken above of incipient albitization. This can be more strongly advanced and lead to the formation of albite-gabbro.

Albite Gabbro

Megascopically the albite gabbros do not differ from the uralite-saussurite gabbros, and in thin sections similar varieties can be distinguished. The plagioclase

is mostly turbid brown with pockets of prehnite and zoisite, with which, in addition, colourless hornblende may be associated. The albite may occasionally be limpid, in which case it is as a rule not twinned. Albitization is far advanced and the An content fluctuates between 0 and 10%. The albite gabbros are more or less uralitized. Occasionally, very strongly pleochroic amphiboles, which cannot be precisely determined, appear as felt-like uralite, which might contain alkali (n_γ brownish-black, n_α light yellow and n_γ bluish-green, n_α reddish-brown). Ilmenite and apatite are ever-present accessory constituents; calcite is found sporadically in fine cracks.

Just as the types of rock of differing mineral content which have so far been dealt with represent a continuous rock series linked by gradations, so there are also transition types between various kinds of texture, and lack of knowledge as to the form and extent of the rock bodies makes the delimitation of, for example, gabbro, dolerite and diabase a highly arbitrary affair. For the purpose of classifying this intermediate position we shall call such rocks here gabbro-diabase.

Gabbro-diabase

The texture is divergent-radial, diabasic to ophitic, mode and colour index vary greatly, as does also the state of preservation. The plagioclase is strongly dull-brown, albitized and prehnitized. Relics of primary, clear plagioclase, of an An content between 35% and 86%, float in turbid brown albitized feldspar with an An content of 0–15%.

The diallage is usually fresh, intergrown with brown hornblende, or partly converted into colourless to bluish-green uralite. Olivine and orthorhombic pyroxene can occur occasionally as additional constituents. Apatite and ore are ever-present accessories.

While the rock types so far described undoubtedly belong to the ophiolites and are in fact very typical representatives and key rocks of this series, this is no longer the case with the following quartz-dioritic rocks.

QUARTZ-DIORITES

The five samples under consideration were collected by Niethammer on the south coast of Kudat Harbour, where they occur together with typical ophiolites (cf. Enclosure IV, Kudat Peninsula). Quartz-dioritic to dioritic rocks also occur in the middle course of the Segama, but there they are associated with crystalline schists. Accordingly, the question as to whether the Kudat quartz-diorites belong to the ophiolite intrusion appears to us not to have been settled, and this circumstance must be borne in mind in discussing the course of the differentiation of the ophiolites.

The quartz-diorites are medium-grained rocks; after strong cataclasis, which is exhibited by two of the samples, they become small-grained to almost compact.

Plagioclase, usually heavily dusted and exhibiting an An content of 1% to 4% only, predominates over quartz among the constituents. No primary mafic minerals occur, but a small quantity of chlorite is always present which gives the rocks a grey-green tinge. Calcite occurs in small veins. A micro-quartz-diorite exhibits porphyritic texture. It is very rich in albite phenocrysts up to 3 mm. in size (4% An), which lie in a microgranitic groundmass of albite, quartz and chlorite, interwoven with veins of calcite.

Two samples were analysed and revealed the following composition:

	Nh. 99	Nh. 95
SiO_2	68·56	55·10
TiO_2	0·43	0·94
Al_2O_3	16·91	19·71
Fe_2O_3	0·54	2·76
FeO	1·10	2·35
MnO	0·07	0·14
MgO	1·06	3·39
CaO	1·66	5·15
Na_2O	6·47	5·14
K_2O	0·58	1·23
H_2O-	0·32	0·12
H_2O+	1·48	3·14
P_2O_5	0·07	0·36
CO_2	0·60	0·95
Total	99·85	100·48
Sp. Gr.	2·61	2·70

Nh. 99: *Leuco-quartz diorite.* (Albite-granite.) South coast of Kudat Harbour. Medium-grained, weakly flaser-gneissose, cataclastic, light greenish-grey. Albite fresh in porphyroclasts and mortar structure; quartz, principally in mortar structure, little pennine and calcite in streaks, occasionally apatite. *Mode* (estimated): 65% albite, 32% quartz, 3% pennine +calcite+apatite. *Analyst:* W. Vögtli.

Nh. 95: *Quartz-diorite*, saussuritic. South coast of Kudat Harbour. Medium-grained, weakly schistose-gneissose-cataclastic, light greenish-grey. The albite is speckled with clinozoisite-sericite microlites. Quartz in mortar structure, scraps of pennine, abundant epidote in nests, apatite and ore as accessories. *Mode:* albite +filling mass (clinozoisite-sericite) 70·5%, quartz 10%, pennine 13·5%, epidote 5%, apatite+ore 1%. *Analyst:* W. Vögtli.

Extrusive Rocks of the Ophiolite Series

Medium- and small-grained to microlitic extrusive rocks are more widespread among the ophiolites than the intrusive rocks dealt with so far, with the possible exception of serpentine, which, as already noted, appears almost regularly where the Danau Formation occurs. On the basis of mineral content and texture, the rock samples examined allow of division into four groups, which are again connected to each other by transition types. These four groups are: diabases, basalts, spilites and ophiolite-breccias and ophiolite-tuffs. Sporadic and aberrant rock types will be discussed with the rock group in connection with which they occur. Diabases, spilites and ophiolitic breccias and tuffs seem to appear with equal frequency and to be

distributed throughout all ophiolite occurrences, while basalts are limited to only a few.

Diabases

The distinction between diabases and basalts was made mainly on the basis of their state of preservation. Among the diabases the pyroxene, which is usually fan-shaped, is often uralitized, and both mafic minerals and plagioclase are more or less strongly replaced by an epimineral content. As chlorite and zoisite-epidote play an essential part among these constituents, the diabases are generally characterized by green colouring. The following data are based on an examination of 67 rock samples and 28 sections.

Typical diabasic texture with diverging radiating feldspars is frequently visible even to the naked eye. Coarser-grained varieties merge into the gabbro-diabases already discussed; finer-grained varieties pass over into microlitic to almost compact sub-types. Brown, limonitic crusts due to weathering and fine cracks filled with quartz or calcite are common phenomena.

The diabases show marked differences in appearance even to the unaided eye, but the diversity becomes far greater when the thin sections are examined. Ophitic texture is less common than radial texture. This passes, in the case of smaller-grained varieties, into intersertal texture; porphyritic texture is not common. The reproductions of thin sections show the principal varieties of texture: Fig. 4, Plate X, exhibits sub-ophitic; Fig. 1, Plate XI, intersertal; and Fig. 2, Plate XI, porphyritic texture.

The lath-shaped plagioclase is mostly covered with brown dust and frequently shows proliferations of prehnite, chlorite and talc, and microlitic inclusions of tiny, colourless hornblende needles and titanite grains. The very strong turbidity frequently prevented an estimate of the An content. Reliable determinations, whether according to the Fedoroff or refractive indices method, could be made only when limpid, probably secondary, albite was present, usually in the chequered form. Albitization is very widespread among the diabases and anorthite contents of 30% to 40% were found only exceptionally, and then not with certainty.

Among the diabases and basalts Carlsbad twinning occurs just as frequently as that after the albite law. Twinning, according to the pericline and acline laws, is less common and the presence of Manebach and complex albite-Carlsbad twinning was established in isolated cases only.

The optical properties of the colourless or faintly greyish to bluish augite (at times still well preserved) vary between the following limits: $n_\gamma - n_\alpha = 0{\cdot}021$ — $0{\cdot}027$; $n_\gamma \wedge c = 40° - 50°$; $+2V\ 40° - 60°$, dispersion $\rho > v$ medium to strong. Arborescent forms and strongly arcuate extinction are widespread, though not so extremely common as among the spilites. Flabelliform augites have intergrown with plagioclase somewhat after the fashion of a myrmekite (visible in the upper right-hand corner of Fig. 4, Plate X). Pigeonite apparently does not occur.

Among the widespread uralite diabases, the pyroxene is partly or wholly replaced by a dirty to bluish-green or colourless, fibrous to reed-like hornblende, mostly speckled in appearance. The measurements yielded $n_\gamma - n_\alpha = 0{\cdot}018 - 0{\cdot}032$; $n_\gamma \wedge c = 9° - 18°$; $-2V \sim 80°$. Besides uralite, epidote usually occurs as well. Olivine is not present, but serpentine pseudomorphs observable in some sections point to an original olivine content.

The colour index ranges within wide limits; next to the most frequently occurring mesocratic types, leucocratic types and less frequently melanocratic types appear.

The mafic minerals, however, have often completely disappeared and been replaced by a secondary epimineral association. Chlorite frequently occurs in the form of rosettes intermingled with leucoxene ovules. Pilite and serpentine occur in pockets and proliferations and gel-like substances, either isotropic or showing faint aggregate polarization, are also present. Without analyser they exhibit the most diverse shades, from reddish-orange through yellow to colourless. The rocks are often impregnated with quartz and calcite, whereby the calcite which frequently appears in hair-like cracks as well, always predominates. A constituent which is never lacking, and often very richly represented, is ilmenite.

Pumpellyite-bearing rocks

A finely fibrous mineral, occurring in fine cracks or amygdules, was encountered in both diabases and spilites, and in one basalt. This mineral could not be identified with certainty as its optical properties appear very changeable and, moreover, could not be definitely determined. The elongation is both + and —, the extinction mainly straight, occasionally also oblique. — 2V appears to vary between 0° and nearly 90°, the maximum birefringence between 0·022 and 0·035. Pleochroism is constantly noticeable, often intense, with n_γ' grass- to bluish-green or yellow, and n_α' light yellow to colourless. Powerfully abnormal interference colours and very strong dispersion of the optical axes $\rho \ll v$ appear to be the only constant properties. The mineral occurs also in a larger aphanitic vein, mottled yellow to blue-green in colour (sample R. 6), in an ophiolite breccia in the Blantian River. A thin section is shown in Fig. 3, Plate X. It is most probably pumpellyite, a mineral which seems to occur quite frequently in Indonesian rocks. De Roever (1947) mentions its presence in various rocks from Celebes and in four different ophiolites of the Danau Formation in Dutch East Borneo.

Analcite-diabase

A single sample (H. 59), from the southern tip of Balambangan Island, has analcite as an essential constituent, replacing the plagioclase (~ 40% An), except for a few tiny remnants. The grey-greenish rock is finely microlitic and strongly protoclastic. The rock was analysed (see p. 74).

The *diabase-porphyrites* are differentiated only texturally from the diabases. Diabase porphyrites do not occur frequently and the porphyritic texture is not very noticeable, except in one sample (Wk. 56) collected by Wenk in the Tungku River on the south coast of the Dent Peninsula, which exhibits plagioclase phenocrysts up to 5 mm. in size, tabular parallel to 010, decomposed into a floury substance, the white colour of which contrasts with the greyish-violet hue of the aphanitic

ground-mass. The thin section is shown in Fig. 2, Plate XI. The completely sericitized and chloritized plagioclase phenocrysts lie in a pilotaxitic ground-mass of sericitized plagioclase microlites and small haematite grains. In other samples augite phenocrysts are also present either alone or in addition to plagioclase phenocrysts.

Amygdaloidal diabase occurs only quite sporadically. Fig. 2, Plate XII, reproduces a thin section of one of them. The amygdules, which are up to 3 mm. in size, filled with calcite and coated with a thin layer of chlorite, lie in a pilotaxitic felt of plagioclase laths and titanaugite in interstices.

Three diabases were chemically analysed. The results are given here, together with one basalt analysis.

H. 78: *Diabase.* Taritipan. SE. corner of Marudu Bay. Greenish-grey, microlitic. Plagioclase laths (albitized), strongly clouded by chloritic proliferations and titanite dust. Augite strongly arcuate extinction, $n_\gamma - n_\alpha = 0{\cdot}026$, $n_\gamma \wedge c = 39°$; $+2V \sim 50°$. In interstices chlorite and ilmenite with leucoxene border. *Mode* (estimated): plagioclase 60%, augite 30%, ore +chlorite 10%. *Analyst:* W. Vögtli.

H. 19: *Basalt.* Pulau Banggi. Dark grey, almost aphanitic. Structure intersertal (Fig. 4, Plate XI). Small plagioclase laths (~ 60% An), very fresh, in the core frequent inclusions of small augite grains or glass, augite in smaller grains and plumose forms as inter-

Chemical analyses of diabases and a basalt

	H. 59	Nh. 12	H. 78	H. 19
SiO_2	47·11	48·27	47·70	47·28
TiO_2	2·01	1·60	1·40	1·73
Al_2O_3	15·51	15·73	13·67	15·36
Fe_2O_3	4·02	3·58	5·15	2·87
FeO	6·05	6·52	5·87	6·88
MnO	0·17	0·20	0·18	0·30
MgO	5·05	6·93	7·86	7·61
CaO	5·92	9·60	10·38	10·65
Na_2O	7·34	4·00	3·58	2·69
K_2O	0·53	0·47	0·05	0·10
H_2O-	1·07	0·39	0·51	1·32
H_2O+	4·81	3·05	3·66	3·07
P_2O_5	0·13	0·14	0·27	0·17
S	0·37	—	—	0·04
F	—	—	—	0·05
Cr_2O_3	0·02	—	—	—
Total	100·11			100·12
Deduction for S	0·14			0·03
Total	99·97	100·48	100·28	100·09
Sp. Gr.	2·65	2·85	2·91	2·82

H. 59: *Analcite-diabase.* Southern point Pulau Balambangan. Grey, finely microlitic, weakly tuffogenous-protoclastic. Plagioclase replaced by analcite down to not exactly determinable residues (andesine). Augite with arcuate extinction. Chlorite in fine scales and magnetite occupy interstices, sporadically pyrite. Measurement on the integration stage is not practicable. *Mode* (estimated): plagioclase+ analcite 70%, augite 27%, ore and chlorite 3%. *Analyst:* J. von Steiger.

Nh. 12: *Albite-diabase.* Tanjong Bangau, Kudat Peninsula, W. coast. Greenish-grey, microlitic, plagioclase laths, interspersed with chlorite scales, albitized. Augite strong arcuate extinction, $n_\gamma - n_\alpha = 0{\cdot}027$, $n_\gamma \wedge c = 34°$; $+2V \sim 45°$. Ore and chlorite in interstices. *Mode* (estimated): plagioclase 55%, augite 35%, ore+chlorite 10%. *Analyst:* W. Vögtli.

stitial matter, arcuate extinction. In interstices brown glass and ore. *Mode* (estimated): 60% plagioclase, 35% augite, 5% ore+glass. *Analyst:* W. Vögtli.

Basalts

No sharp separation can be made between diabases and basalts. If the state of preservation had been the only factor in making a division, the result would have been highly arbitrary. The rocks distinguished here from the diabases as basalts are either quite fresh or their secondary minerals exhibit a character other than that found in the diabases. Moreover, the augite exhibits no, or at most weakly, arcuate extinction and no arborescent forms such as are typical for the diabases. The good state of preservation is already evident in the colour of the basalts, mainly dark grey with very occasionally a greenish tinge, and the secondary mineral formation, differing as it does from that of the diabases, frequently gives them a brownish tint. Brown,

limonitic crusts due to weathering also seem to be limited to the basalts.

The plagioclase is, as a rule, as clear as glass and strongly zoned. The anorthite content then varies within very wide limits between core and outer shell (81% to 50% An; 51% to 24%; 64% to 27%; 60% to 30%). The anorthite content of the individual grains varies between 50% and 70%. In porphyritic texture, which occurs rarely, the plagioclase phenocrysts are occasionally replaced by calcite-chlorite pseudomorphs. Apart from the arcuate extinction, the augite exhibits the same optical properties as those of the diabases. In one rock, felt-like hornblende, a dirty olive-green in colour, occurs in interstices together with talc. A brownish-black, decomposed glass is found widely disseminated as interstitial material. Ore is a common accessory constituent; calcite occurs in cracks. A small vein with acicular natrolite from a basalt outcrop (Tanjong Bangau) is to hand.

The texture varies from sub-ophitic in the case of doleritic basalts (Fig. 3, Plate XI) through intersertal (Fig. 4, Plate XI) to hyalopilitic (Fig. 1, Plate XII). The last illustration furnishes an example of porphyritic and amygdaloidal structure. The amygdules are filled with a finely acicular mineral which might be pumpellyite, judging by optical properties which could only be imperfectly ascertained.

Basalt occurrences are limited to a few areas. Two samples come from the islands off the northern tip of Borneo (H. 4 and 19, Enclosure III). In what association they occur there is not known. In Tanjong Bangau (cf. Enclosure IV) basalts occur in conjunction with typical Danau ophiolites (serpentine, diabase, spilite) and radiolarian cherts.

It is questionable whether the basalt occurrences on the east coast of the Bengkoka Peninsula, in the River Kuamut and in other tributaries of the Kinabatangan, belong to the Danau ophiolites or not. As the question is of great importance in connection with the determination of the age of the Danau ophiolites, it will be touched upon once again in the relevant chapter.

Spilites and associated rocks

The separation of the spilites from diabases and basalts was made in the first place on the basis of texture. The mineral content was considered only in so far as the attempt was made to class as spilites solely those rocks whose plagioclase is albite or, at any rate, very poor in anorthite content. The spilites might therefore be defined as microlitic albite diabases or albite basalts. As the finely-microlitic grain frequently prevented the feldspar from being determined, we are inclined to doubt whether only those rocks which include albite are to be found among those we classed as spilites. Another distinguishing mark of the spilites is their amygdaloidal structure, which is only rarely absent. Both typical characteristics—finely microlitic, amygdaloidal structure—are clearly to be seen in Figs. 3 and 4, Plate XII. Varioles, on the other hand, seem to be rare. Only one variolitic spilite is present among the 75 spilite samples, of which 56 were examined in thin section. Strangely enough, pillow-structure seems to occur only rarely, although it is otherwise so frequently found among the spilites that spilite and pillow-lava pass for synonyms. Stamm and Niethammer mention it occasionally; Wenk established its presence in the Malua; Reinhard did not encounter it, in spite of the wide distribution of spilites in the Blantian River area which he explored.

The rocks, which appear to the naked eye to be anything between aphanitic and finely microlitic, vary in colour from light to dark grey, greenish-grey and violet-grey. The spilites are often splintery and interpenetrated by slickensides filled with specular haematite. Calcite or ochreous limonite occur very often in cracks; zeolites are somewhat less common. Brown limonitic weathered surfaces allow the presence of a not inconsiderable iron-content to be assumed.

The rocks are often either crowded with minute amygdules, or show fewer and larger amygdules whose diameter varies between 0·1 mm. and 10 mm. The amygdaloidal mineral most frequently met with is calcite; chlorite (chiefly delessite) occurs almost as often. The presence only of isolated occurrences of aragonite, quartz, opal, albite, zeolites, epidote, hornblende and (possibly) pumpellyite was established.

The texture varies between pilotaxitic, hyalopilitic and trichitic. The occasional appearance of sporadic phenocrysts indicates a faintly porphyritic development. The phenocrysts are generally completely altered into calcite, chalcedony, opal, zeolites or chlorite. Where relics are still present, usually in the form of narrow borders, they are generally of feldspar or, less often, of augite. Sometimes the shape suggests olivine; no relics of this mineral, however, could be detected.

The feldspar ground-mass consists of plagioclase laths which, judging by their refraction, are usually very rich in albite. The small laths are often denticulated at the ends and show stringers of chlorite and calcite or titanite granules along their longitudinal axes. In the case of trichitic spilites the albite appears in arborescent and spherulitic forms. Only albite twins seem to occur.

The augite is colourless or faintly brownish-violet; in the latter case it probably is titaniferous. The optical properties vary within the same limits as in the case of the diabase augite; pigeonite, however, occurs occasionally in the spilites, with an axial angle $+2V$ 20°–30°. The arcuate extinction and the tendency to form arborescent crystal patterns are still more conspicuous and extremely widespread among the spilites than among the diabase pyroxenes. De Roever (1940) describes " arcuate extinction and a feathery or plumose growth " in the augite of the ophiolitic rocks of the Moetis region in Netherlands Timor. These properties in spilite augites have been mentioned by several authors, and they attracted the attention of Dana when he was examining the Hawaii basalts. As appears from the description of the Simporna volcanic rocks, arcuate extinction is also very common in the pigeonite augites of the andesites.

The proportion of albite to augite is subject to great fluctuations. In a few cases the augite predominates over the plagioclase and the augite content may be as much as 80%. The spilites with albite predominating are much more frequent, and it is not uncommon for pyroxene to be completely absent. Brown primary hornblende and uralite occur exceptionally.

The albite and augite microlites are usually embedded in a light-greenish to colourless ground-mass of chlorite in fine scales in which, besides titanite, always very abundant, titaniferous iron-ore and, rarely, apatite are also present. Calcite is very common in pockets and proliferations; serpentine and bowlingite occur only sporadically. Feldspar and pyroxene in bunches are occasionally found floating in a brown, ore-dusted glass, which passes locally into a finely-flaked chlorite mass. Mineral transformation during or after the ultimate stage of consolidation is more common among the spilites than the diabases. Apart from the very widespread chlorite impregnation already mentioned, more localized epidotization, zeolitization and limonitization take place. Calcification and silicification are again so widespread and give rise to such typical developments that a special chapter will be devoted to them.

When a fluidal development is present, the fabric becomes trachytic. Some samples of such trachytic spilites have been collected by Hotz in the Batu Matindok gorge in the upper course of the Kadamayan, on the SW. slope of Mt. Kinabalu (H. 123). These spilites consist of small laths of albite, dusted with chlorite, titanite and ore, and exhibit fluidal texture. Two greyish-violet, compact spilites collected by Stamm in the Segama (St. 190 and 191, cf. Enclosure VIII) exhibit even more pronounced trachytic texture. The fine albite laths form some 65% of the rock. They are finely denticulated by small ore granules and chlorite flakes. A very few mottled albite phenocrysts, up to 2 mm. in size, are full of chlorite proliferations; augite appears in a few granules only. Calcite and radially fibrous chlorite occur in tiny amygdules. But what especially differentiates both samples from the rest of the spilites is the occurrence of a mica possessing quite striking optical properties. Pleochroism is not very powerful, n_γ yellowish-greenish, n_β reddish-brown, n_α light pink, $n_\gamma - n_\alpha = 0{\cdot}050 - 0{\cdot}058$, $-2V \sim 20°$; dispersion $\rho \ll v$ unusually powerful. Sections perpendicular to the acute bisectrix show an anomalous dark greenish-blue interference colour and dark-brown extinction. Twins on 001 are conspicuous. Extinction n_γ : twinning planes (001) $\sim 4°$. The mica lamellae, which are up to 0·2 mm. in size, are generally surrounded by chlorite in fine flakes. The mica content does not exceed 2% by volume in either of the two samples.

The only specimen of a *keratophyre* (St. 189 from Pulau Ta, Segama, cf. Enclosure VIII) comes from the immediate neighbourhood of these micaceous trachytic spilites. The rock can be differentiated megascopically from the spilites by its coarser grain and its light-reddish, green-speckled appearance. The texture is typically trachytic, with turbulent flow, as Fig. 1, Plate XIII shows. The finely denticulated albite laths, often grouped in fascicles, are a very marked turbid brown; they form the bulk of the rock. Poorly individualized aegirine crystals are embedded in small pockets of a microlitic hornblende felt. Apart from the brown dustiness of the albite the rock is still very fresh, and the question arises as to whether it should be classed as trachyte (aegirine-soda trachyte) or as keratophyre. Chemical analysis revealed a high alumina content, and the calculation of the Niggli values showed a correspondingly high degree of excess alumina, which, owing to the strong turbidity of the albite, was to be expected.

Hyalo-potash-rhyolite

A dense, light bluish-green rock intersected by limonitic cracks (J. 154) was collected by Jezler in the Batu Tatak River, a small tributary on the right bank of the lower Segama, 23 km. NNE. of Lahad Datu. In a glassy perlitic ground-mass, with localized weakly microfelsitic devitrification, mottled zonal phenocrysts of plagioclase up to 4 mm. long and quite pale brown in colour are sporadically embedded. Determination on the universal-stage revealed an An content of 2% to 6% and Ala twinning.

The following table gives data regarding the chemical composition of the spilites and associated rocks.

Chemical Analyses of Spilites and Associated Rocks

	R. 26	R. 7	Nh. 199	H. 123	St. 189	J. 154
SiO_2	44·89	49·30	50·72	51·52	62·10	65·84
TiO_2	4·06	1·04	1·29	2·00	0·15	0·65
Al_2O_3	15·80	12·89	15·37	15·14	21·25	15·46
Fe_2O_3	1·40	3·72	1·69	8·00	2·26	2·66
FeO	9·10	3·79	6·61	2·02	1·47	1·46
MnO	0·08	n.d.	0·14	0·22	0·13	0·17
MgO	4·76	3·97	7·66	7·22	0·91	0·11
CaO	5·44	10·49	9·04	3·84	0·19	0·28
Na_2O	5·53	5·59	6·04	5·44	7·69	5·02
K_2O	0·18	2·05	0·71	0·18	2·30	5·58
H_2O-	0·52	0·98	0·60	0·70	0·41	0·95
H_2O+	4·94	4·07	0·58	4·07	1·32	1·83
P_2O_5	1·10	—	0·08	0·16	0·06	tr.
CO_2	2·80	2·82	tr.	tr.	—	—
Cl	—	n.d.	n.d.	n.d.	n.d.	tr.
	100·60	100·71	100·53	100·51	100·24	100·01
Sp. Gr.	2·51	2·62	2·96	2·71	2·72	2·42

Chemical analysis showed a considerable K_2O content in contrast with the ophiolites, which are always rich in soda and whose potash content is small to negligible. According to the chemical composition and the appearance in thin section, the rock is a hyalo-potash rhyolite (= hyalo-pantellerite). Spilites occur in its vicinity and radiolarian cherts and a peridotite are found not far away. Association with typical rocks of the Danau Formation seems to point to a genetic relationship, and as no samples of Miocene volcanic rocks from the area are available, with the exception, perhaps, of a not very typical crystal tuffite, this potash-rhyolite would appear to belong to the ophiolitic differentiation products and not to the Tertiary volcanic rocks. However, we regard this question as still open.

R. 26: *Spilite.* Blantian River. Light greenish-grey, aphanitic, calcite amygdules up to 2 mm. in size. Calcite likewise in small cracks. Texture pilotaxitic-hyalopilitic (Fig. 3, Plate XII). *Mode* (estimated): 70% albite, 20% ore+titanite+chlorite, 10% calcite. *Analyst:* W. Vögtli.

R. 7: *Spilite.* Blantian River, finely microlitic, much calcite, occasionally quartz amygdules. Texture pilotaxitic, somewhat coarser grain than R. 26, like R. 26 in mineral composition, rather more calcite, augite remnants in minute granules. *Analyst:* H. Preiswerk.

Nh. 199: *Diabase spilite.* Bukit Tampasuk, 2½ km. east of Kota Belud. Dark greenish-grey, finely microlitic. Texture pilotaxitic to micro-ophitic. Plagioclase laths rendered markedly turbid by small flakes of chlorite; according to refraction rich in albite. Pigeonite (+2V = 20°–30°) in grains and arborescent groups, arcuate extinction particularly strong. Chlorite with titanite in interstices. *Mode* (estimated): 50% albite to oligoclase, 45% pigeonite, 5% chlorite+titanite. *Analyst:* J. von Steiger.

H. 123: *Spilite, trachytic.* Batu Matindok Gorge, upper Kadamayan, SW. slope of Kinabalu, dark greyish violet, compact, with haematite coated slickensides. Texture trachytic, weakly fluidal. Small albite laths with ore, titanite and chlorite dust. Blackish-brown ore in small grains and skeletons. Few chlorite amygdules, sporadic quartz grains. *Mode* (estimated): 70% albite, 30% chlorite +ore+titanite. *Analyst:* W. Vögtli.

St. 189: *Keratophyre* (aegirine-soda-trachyte). Segama River, Pulau Ta. Fine-grained, light reddish, mottled with green. Trachytic-fluidal texture. Albite laths, fluidal or in fascicular aggregates, deep cloudy brown. Aegirine in interstices surrounded by finely felted hornblende. *Mode* (measured): 76% albite, 7% aegirine, 17% felted hornblende. *Analyst:* W. Vögtli.

J. 154: *Hyalo-potash-rhyolite* (=hyalo-pantellerite). Batu Tatak River, right-hand tributary of the lower Segama. Light bluish-green, compact, with ochreous cracks. Texture vitro-porphyritic. Sporadic albite phenocrysts (2% to 6% An) in a perlitic glassy groundmass. *Mode* (measured): glass 98%, albite phenocrysts 2%. *Analyst:* P. Esenwein.

Ophiolitic breccias, tuffs and tuffites

It has already been mentioned that a single kind of rock is but rarely present in occurrences of ophiolite; instead, various types of ophiolite appear together, very often as a giant breccia whose component blocks have a magnitude of the order of cubic metres. But other breccias also are common, of which the components are considerably smaller, and which may be recognized as polygenous rocks not only in outcrops but also in the hand sample. Such breccias and tuffs are also very characteristic of the Danau ophiolites of Dutch Borneo, and have passed into the literature on the subject as Pulu Melaiu breccias.

The attempt to separate the ophiolitic tuffs from the adinoles resulted in great uncertainty, as lack of data concerning the type of occurrence confined investigations exclusively to the thin sections and the appearance of the rock samples. Fifty-three samples, of which 32 were examined in thin section, were classified as breccias and tuffs.

Ophiolitic breccias and tuffs are very widely disseminated. Almost everywhere where diabase and spilite occur, breccias and tuffs derived from similar material are present.

The *ophiolite-breccias* are rocks of various shades of green. The colouring is uniform among *monomict*, but variegated among *polymict* breccias. In the case of the samples examined in thin section, the elements vary in shape from angular to, at most, round-cornered, and in size between that of a pea and that of a nut. The spilites seem to have had quite a marked tendency to form breccias, as appears from the almost complete predominance of spilitic components over others. Frequently only relics, or even nothing at all, is left of the original mineral content of the spilites. The texture, however, has been preserved in all its finer details, despite the thorough recrystallization. The finely-microlitic to trichitic, more rarely vitrophyric, varieties predominate over the more coarsely crystalline. The tiny augite fans are wholly or partly limonitized and the plagioclase trichites altered into chlorite; the whole is peppered with small grains of titanite. The brecciated elements may be welded together without the intervention of a cementing agency, or they may lie embedded in a cement formed very often of calcite, aragonite and chalcedony, in which zeolites, chlorites and prehnite may appear.

Only one sample each of *uralite-diabase-breccia* and *gabbro-breccia* are present. The uralite of the diabase-breccia is mottled dirty to bluish-green, $n_\gamma - n_\alpha = 0{\cdot}021 - 0{\cdot}027$, $n_\gamma \wedge c = 17°$; $-2V \sim 80°$. The reedy hornblende is associated with clinozoisite-epidote. The plagioclase is completely altered into zeolite, and zeolites are also to be found in clusters and small cracks. Ore is scantily represented, leucoxene plentifully. The plagioclase of the gabbro-breccia is a marked muddy-brown in colour and speckled throughout with small colourless to bluish-green hornblende needles. The diallage is almost completely altered into a felt of uralite, epidote and calcite. A reaction rim of

blue-violet, glaucophane-like amphibole is occasionally found between plagioclase and diallage, mixed with grains of a grass-green hornblende and a chlorite of the same colour.

In the polymict breccias, chert and limestone also occur as components in addition to the spilites. A fragment of a compact limestone is interspersed with small twinned albite crystals which are up to 0·2 mm. in length, idiomorphic, elongated along the a axis or tabular after 010, polysynthetic according to the albite law (1–4 lamellae), and clear as glass.

A *conglomeratic breccia* of a remarkable type was encountered by Roothaan and Wenk in the River Karamuak, a left-bank tributary of the Milian (Kinabatangan). The breccia and pebble components consist of gneiss and sediments lying embedded in an ophiolitic matrix.

As the size of grain diminishes (smaller than 5 mm.) the monomict breccias pass over into tuffs and the polymicts into tuffites. The rocks are aphanitic or finely to coarsely arenaceous, stratification is occasionally indicated.

The finely microlitic spilites, often completely replaced by calcite and chlorite, dusted with titanite, predominate once more among the components of the *lithic tuffs* to *tuffites*. Uralite-diabases, radiolarian cherts and limestones occur as further components. The tuffs are usually impregnated with quartz, calcite, limonite, chlorite and zeolites. Figs. 2 and 3, Plate XIII, provide illustrations of such lithic tuffs.

Plagioclase, augite, hornblende, epidote and quartz occur as mineral components among the *crystal-tuffites*. They lie embedded in a calcite-chlorite cement which may be more or less impregnated with limonite.

No glass is preserved in any of the tuffogenic rocks. But taking texture as a criterion, *vitric tuffs* are present whose originally vitreous base has been completely chloritized with still visible perlitic texture.

Tuffitic limestones are very common. All gradations are to be found, from types poor in calcite to almost pure sandy limestones. The carbonate content in these rocks is of primary origin and arose through contemporaneous sedimentation with the tuffogenic constituent. However, calcified tuffs in which the calcite is not a primary constituent, but was added later, are also very common. As tuffitic limestone can also be subsequently calcified, both types are connected with each other through transition members.

Ophiolites versus Spilitic Suite

As has already been mentioned, the ophiolites of North Borneo show few signs, if any, of dynamo-thermal metamorphism. The rocks are massive throughout, apart from purely localized foliation. Perlitic structure, fragile arborescent plagioclase crystals and augite trichites, which are extremely susceptible to shearing stress, are entirely undamaged. Their excellent state of preservation precludes differential movements in the solid rock. The widespread arcuate extinction of the augites among the diabases and spilites is not the result of cataclasis, but has ensued from the conditions obtaining during crystallization (rapid growth) and from the composition of the melts.

The well-known classical ophiolite occurrences (Alps, Apennines, Dinaric Alps, Carpathians) are associated with mountain chains. As their intrusion into the geosynclinal sediments took place before the main paroxysm of the folding, they were caught up by the later orogenic movements and, in so far as they lay in deeper nappes, altered by dynamo-thermal metamorphism.

The Borneo ophiolites differ from those involved in the Mediterranean orogenesis in that they are not associated with an orogenic belt of alpine type and so have not experienced comparable metamorphism. The rock group which, notwithstanding this fact, we here term ophiolites, also exhibits a close affinity with the " spilitic suite " of Dewey and Flett (1911), which the two authors postulate as being distinct from the Atlantic and Pacific provinces. This is certainly a mistake. Atlantic and Pacific provinces, and the Mediterranean province added by Niggli, differ petrochemically from each other and, in consequence, also in the manner of their differentiation. As has been proved by Burri and Niggli (1945), to whom we owe the latest and most exhaustive comparative petrochemical monograph yet produced on the ophiolites and basic magmas in general, this is not the case with the " spilitic suite ". Nevertheless, a collective name is necessary for these typical and common rock associations, ably differentiated for the first time by Dewey and Flett. The extension of the name of one rock to cover a whole association of rocks, even when the denominating rock is an ever-present, characteristic member of the series, does not strike us as a happy solution. Accordingly we have, with considerable hesitation, given preference to the designation " ophiolites " rather than to " spilitic suite ", introduced by Dewey and Flett. These two authors state that " the ophiolitic eruptives " of Steinmann are not co-extensive with the spilitic suite, but they omit to indicate the differences between them.

Is the Mineral Content of the Ophiolitic Rocks of North Borneo Primary Magmatic or Autometamorphic?

As has just been stated, the epi-mineral content characteristic of many ophiolitic rocks cannot be ascribed to dynamo-thermal metamorphism. A further problem arises as to whether the mineral content is primary magmatic or owes its origin to autometamorphic processes. Investigators concerned with ophiolitic-spilitic rock associations have, almost without exception, attached great importance to the question of the primary or secondary origin of the mineral content. This has even led to the separation of the weilburgites, originating " through immediate crystallization from a magma ", from the spilites, which are mineralogically

and texturally identical with them, because " in petrography the term spilite is understood to mean an autometamorphic diabase " (Lehmann, 1941, pp. 30, 31). To follow this proposal would have unfortunate consequences, because two more new names would have to be introduced, one for " spilites " of mixed mineral genesis, the other for those in which it cannot be established whether their mineral content is primary or secondary. It is certainly more convenient to rest content with one name, for the question of the primary or secondary nature of the mineral constitution is in this case quite unimportant. All investigators agree that the ophiolitic-spilitic residual magmas must have been characterized by a particularly high content of water and carbonic acid. This abundance of volatile constituents must have lowered the crystallization temperature considerably, and from such low-temperature solutions and emulsions, albite-diabases and spilites primarily originate. The excess gases and vapours, liberated during crystallization, attack the mineral components of the already consolidated rocks at a higher temperature; these components are then modified to fit the new temperature-pressure conditions. Rocks of primary, and those of autometamorphic, epi-mineral, composition must therefore occur next to, and merge into, one another. Genetically they are correlates and owe their origin to the same rock-formative process. Burri and Niggli (op. cit., 1945) have summarized the problem excellently in the chapter on spilite associations (pp. 495, 496) in their monograph: " Whether certain rocks crystallized directly from such low-temperature magmas of high-water content, whereby some of the earliest separation products may have been altered, or whether the residual solution effected the (autometamorphic) alteration of the mineral composition after major crystallization had already taken place, is probably not of such fundamental importance as is often supposed. For in both cases the processes belong to the history of magma solidification, and in both cases the phase rich in volatile constituents was magmatic in origin." (Translated from the original German.)

These statements not only have a bearing on the diabases and spilites, but are also valid for the serpentine, which can be crystallized primarily from a serpentine magma after the water content of the peridotite melt has attained the necessary degree of concentration, as has already been assumed by various investigators (Daly, Gisolf, Hess). But early precipitated olivine can also become autometamorphically hydrated during a later phase. The secondary nature can be easily recognized by the serpentine pseudomorphs after olivine. Many petrographers will have noted with surprise Bowen's view (1947) that the absence of large, well-formed serpentine crystals, similar to the crystals of miarolitic-pegmatitic druses in granite, testifies against the presence of a serpentine magma.

In describing the ophiolites, aberrant local varieties have occasionally been referred to in connection with the category of rocks with which they appear, as, for example, in the paragraph on serpentine, where talc-chlorite-zoisite and epidote rocks, and nephrite and jadeitite have been described. We are probably not dealing here with primary magmatic products. As more precise details of their mode of occurrence were not available, the question of their origin has had to be left open.

Petrochemical Characteristics of the Ophiolites

In so far as sufficient fresh material was to hand, the principal types of the ophiolitic rocks of North Borneo were subjected to exhaustive chemical examination. Fifteen ophiolites, one contact rock and two quartz diorites* of questionable affinity, as set out in Table VIII, were chemically analysed by P. Esenwein, H. Preiswerk, J. von Steiger and W. Vögtli. This chemical investigation was justified by the wealth of material, by the fact that it concerned the prototype of an ophiolite-spilite suite associated with siliceous sediments, and by the fortunate circumstance that the rocks have not suffered dynamo-thermal metamorphism; hence the original magmatic to autometamorphic composition is still preserved. Thanks to these qualities, the Borneo ophiolites form an exceptionally favourable object of study and yield valuable comparative material for the understanding of the metamorphic ophiolite series, whose structure and texture, mineral constitution and possibly chemical composition as well, have been subsequently altered by orogenic metamorphism. The chemical data published here might also, at a later stage in the geological-mineralogical exploration of North Borneo, be of economic interest, as all occurrences of ore in the country appear to be associated with ophiolitic bodies.

*The hornblende-quartz-diorite L. 103 has been included in the table of the ophiolites as the only analysed representative of the crystalline basement.

The methods of calculation and presentation introduced and long established on the Continent by Niggli (1919, 1936b, Burri-Niggli, 1945), and which have lately found acceptance also in North America, have been employed throughout in discussing the chemical relations. The application of Niggli's methods was all the more suitable since Burri and Niggli (1945) have dealt exhaustively with the ophiolites of the Mediterranean orogenic belt according to this system, and so the analogous treatment of Indonesian ophiolites offered welcome opportunities for comparison.

List of pre-Tertiary rocks included in Tables VIII and IX

R. 44: Plagioclase-bearing serpentinized dunite. Blantian River, south-eastern part of North Borneo. Analysis by P. Esenwein.

R. 38: Troctolite, medium-grained, streaky. Blantian River. Analysis by H. Preiswerk.

R. 22: Olivine-gabbro, medium-grained, banded. Blantian River. Analysis by H. Preiswerk.

R. 24: Olivine-gabbro, medium-grained. Blantian River. Analysis by P. Esenwein.

J. 202: Uralite-gabbro-diorite. S.Subahan, Darvel Bay, east coast. Analysis by P. Esenwein.

H. 59: Analcite-diabase. Tg. Kalutan, Balambangan Island, off the northern point of Borneo. Analysis by J. von Steiger.

H. 19: Basalt, fine-grained. Between Laksiang and Limbuak, eastern part of Banggi Island, off the northern point of Borneo. Analysis by W. Vögtli.

H. 78: Basalt, doleritic. S.Taritipan, south-east coast of Marudu Bay, northern part of North Borneo. Analysis by W. Vögtli.

Nh. 12: Albite-diabase. Tg. Bangau, Kudat Peninsula, northernmost part of North Borneo. Analysis by W. Vögtli.

R. 26: Spilite, brecciated, with small amygdules and veinlets of calcite. Blantian River. Analysis by W. Vögtli.

R. 7: Spilite, microlitic, slightly brecciated, with amygdules and veinlets of calcite. Blantian River. Analysis by H. Preiswerk.

Nh. 199: Spilite. Bukit Tampassuk, near Kota Belud, northern part of the west coast. Analysis by J. von Steiger.

H. 123: Spilite, trachytic. Batu Matindok, S.Kadamayan, SW. of Mt. Kinabalu, west coast. Analysis by W. Vögtli.

St. 189: Keratophyre = aegirine-soda-trachyte. Pulau Ta, Segama River, east coast. Analysis by W. Vögtli.

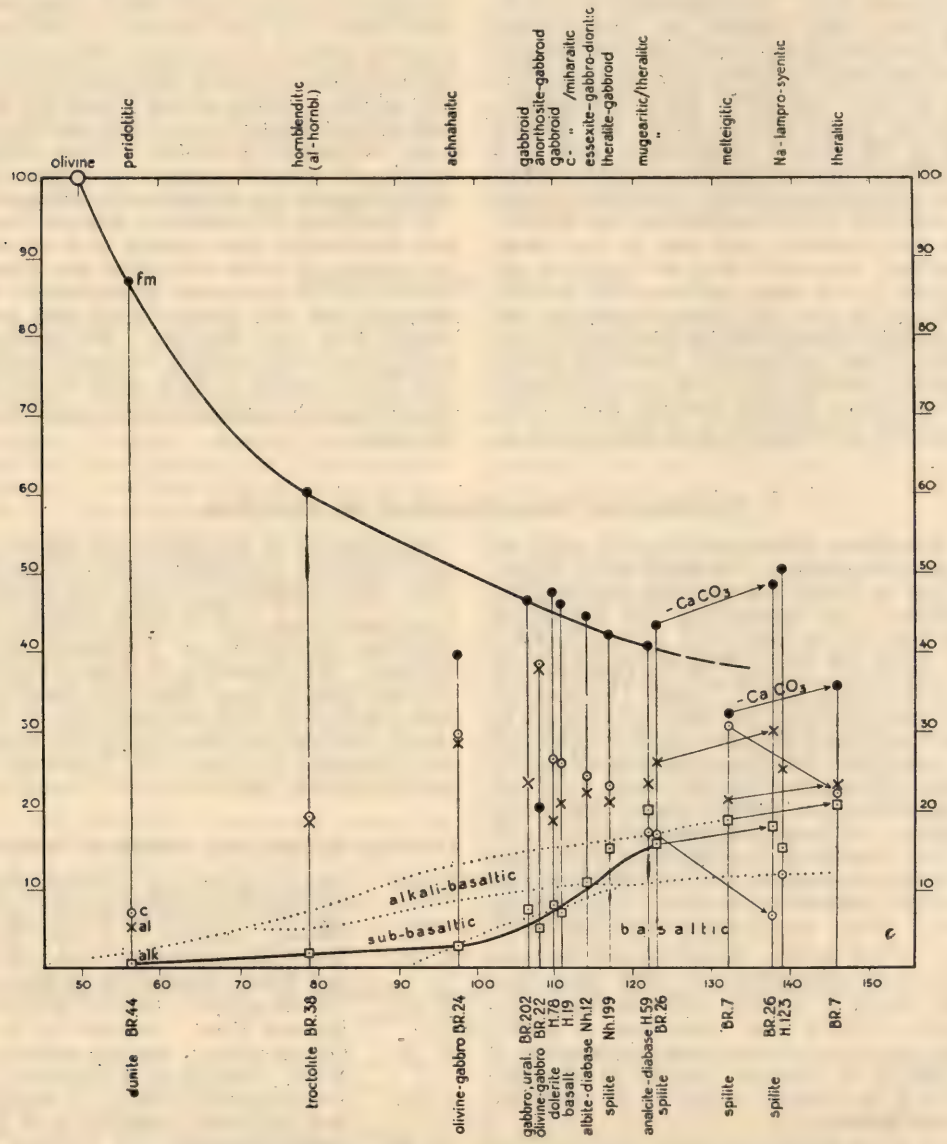


Fig. 21. Variation diagram of the ophiolitic suite of the Danau Formation

For explanation see Fig. 9, p. 40

TABLE VIII. CHEMICAL ANALYSES OF PRE-TERTIARY ROCKS: 15 OPHIOLITES AND 1 CONTACT ROCK OF THE DANAU FORMATION AND 3 QUARTZ-DIORITES OF UNCERTAIN PARENTAGE

	R. 44	R. 38	R. 22	R. 24	J. 202	H. 59	H. 19	H. 78	Nh. 12	R. 26	R. 7	Nh. 199	H. 123	St. 189	J. 154	Nh. 240	Nh. 95	Nh. 99	L. 103
SiO_2	36·34	41·46	46·17	46·33	45·31	47·11	47·28	47·70	48·27	44·89	49·30	50·72	51·52	62·10	65·84	33·57	55·10	68·56	66·03
TiO_2	tr.	0·14	0·13	0·32	3·16	2·01	1·73	1·40	1·60	4·06	1·04	1·29	2·00	0·15	0·65	0·55	0·94	0·43	0·53
Al_2O_3	6·18	16·29	27·16	22·60	16·53	15·51	15·36	13·67	15·73	15·80	12·89	15·37	15·14	21·25	15·46	21·49	19·71	16·91	16·63
Fe_2O_3	2·89	4·74	1·64	1·03	8·33	4·02	2·87	5·15	3·58	1·40	3·72	1·69	8·00	2·26	2·66	11·62	2·76	0·54	1·51
FeO	5·80	3·37	0·88	3·18	6·26	6·05	6·88	5·87	6·52	9·10	3·79	6·61	2·02	1·47	1·46	1·65	2·35	1·10	1·77
MnO	0·04	0·12	0·01	0·06	0·11	0·17	0·30	0·18	0·20	0·08		0·14	0·22	0·13	0·17	0·24	0·14	0·07	0·10
MgO	32·86	16·97	4·55	10·16	5·44	5·05	7·61	7·86	6·93	4·76	3·97	7·66	7·22	0·91	0·11	2·51	3·39	1·06	1·63
CaO	4·40	9·35	15·24	12·84	8·96	5·92	10·65	10·38	9·60	5·44	10·49	9·04	3·84	0·19	0·28	20·46	5·15	1·66	4·48
Na_2O	0·34	1·19	1·92	1·40	2·97	7·34	2·69	3·58	4·00	5·53	5·59	6·04	5·44	7·69	5·02	0·66	5·14	6·47	4·40
K_2O	0·05	none	0·03	0·52	0·48	0·53	0·10	0·05	0·47	0·18	2·05	0·71	0·18	2·30	5·58	0·43	1·23	0·58	1·27
H_2O+	11·08	6·33	2·43	1·37	2·71	4·81	3·07	3·66	3·05	4·94	4·07	0·58	4·07	1·32	1·83	6·51	3·14	1·48	1·07
H_2O-	0·19	0·49	0·16	0·13	0·16	1·07	1·32	0·51	0·39	0·52	0·98	0·60	0·70	0·41	0·95	0·36	0·12	0·32	0·16
P_2O_5	tr.	0·05	0·23	tr.	tr.	0·13	0·17	0·27	0·14	1·10	none	0·08	0·16	0·06	tr.	0·08	0·36	0·07	0·19
CO_2	none	none	none	none	none					2·80	2·82	tr.	tr.		none	none	0·95	0·60	
Cl	0·14	none	none	tr.	tr.					none					tr.				
F						none	0·05	none	none										
S		0·15	none	none	none	0·37	0·04	none	none										
Cr_2O_3		0·06	none	none	none	0·02	none	none	none										
BaO										tr.									
Total	100·31	100·71	100·55	99·94	100·42	100·11	100·12	100·28	100·48	100·60	100·71	100·53	100·51	100·24	100·01	100·13	100·48	99·85	99·77
— O for S & F		0·07				0·14	0·03												
		100·64				99·97	100·09												
Sp. Gr.	2·76	2·75	2·76	2·90	2·89	2·65	2·82	2·91	2·85	2·51	2·62	2·96	2·71	2·72	2·42	3·20	2·70	2·61	2·67

TABLE IX. MOLECULAR BASE AND NIGGLI VALUES OF PRE-TERTIARY ROCKS: OPHIOLITES AND CONTACT ROCK OF THE DANAU FORMATION AND QUARTZ-DIORITES OF UNCERTAIN PARENTAGE

No.	Q	L	M	Sp+Hz+C	Ru	Cp	π	k	γ	mg	α	si	al	fm	c	alk	ti	co_2	Magma type	Rock name
R. 44	6·5	11·3	82·2	—	—	—	·82	·1	·02	·88	−0·038	56	5·5	87	7	0·5	—	—	peridotitic	serpentinized dunite
R. 38	21·4	30·8	47·7	—	0·1	—	·79	—	·05	·80	+0·054	79	18·5	60·5	19	2	0·5	—	hornblenditic	troctolite
R. 24	29·9	41·4	28·5	—	0·2	—	·78	·20	·10	·82	+0·24	98	28	39·5	29	3·5	0·5	—	achnahaitic	olivine-gabbro
J. 202	26·8	37·6	33·3	—	2·3	—	·51	·09	·13	·41	+0·146	107	23	46·5	23	7·5	5·7	—	gabbroid/c-gabbroid	uralite-gabbro-diorite
R. 22	34·6	49·8	14·9	—	0·1	0·6	·79	·01	·18	·78	+0·27	108	37·5	20	38	4·5	0·3	—	anorthosite-gabbroid	olivine-gabbro
H 78	26·2	33·4	38·8	—	1·0	0·6	·40	·01	·23	·57	+0·29	110	18·5	47·5	26	8	2·4	—	gabbroid	basalt, doleritic
H. 19	28·8	34·2	35·8	—	1·2	—	·54	·02	·21	·58	+0·50	111	21	46	25·5	6·5	3·0	—	c-gabbroid/miharaitic	basalt
Nh. 12	26·6	38·3	33·7	—	1·1	0·3	·38	·07	·21	·55	+0·09	114	22	44	24	10	2·8	—	essexite-gabbro-dioritic	albite-diabase
Nh. 199	23·0	41·7	34·4	—	0·9	—	·18	·08	·27	·62	−0·41	117	21	42	22·5	14·5	2·2	—	theralite-gabbroid	spilite
H. 59	21·3	47·9	29·1	—	1·4	0·3	·10	·05	·22	·48	−1·04	122	23·5	40·5	16·5	19·5	3·9	—	theralitic/mugearitic	analcite-diabase
R. 26	25·7	44·3	24·6	—	3·1	2·3	·26	·02	·04	·45	−0·38	123	25·5	43·5	16	15	8·4	10·0	mugearitic	spilite
*R. 26	28·6	36·3	19·8	9·8	3·2	2·3	·06	·02	·00	·45	+0·38	138	28·5	48·5	6	17	9·4	—		spilite
H. 123	30·0	41·1	27·2	—	1·4	0·3	·25	·02	·02	·58	+0·27	139	24	50·5	11	14·5	4·1	—	na-lamprosyenitic	spilite
R. 7	24·3	42·3	32·6	—	0·8	—	·06	·19	·47	·50	−0·35	132	20·5	31·5	30	18	2·0	10·0	melteigitic	spilite
*R. 7	27·2	43·9	28·1	—	0·8	—	·06	·19	·35	·50	−0·21	147	22·5	35·5	22	20	2·3	—	theralitic	spilite
St. 189	39·6	49·3	2·3	8·7	0·1	—	·01	·17	·00	·30	+18·2	239	48	17	1	35	0·5	—	bostonitic/pulaskitic	keratophyre
J. 154	45·1	48·8	4·4	1·2	0·5	—	·02	·42	·00	·05	+6·18	308	42·5	16·5	1·5	39·5	2·3	—	alkali-granitic/k-nord-markitic	hyalo-pantellerite
Nh. 240	20·2	42·0	37·4	—	0·4	—	·87	·30	·42	·27	−0·62	68	25·5	28	44·5	2	0·9	—		chert-like contact rock
Nh. 95	36·9	48·3	13·0	0·4	0·7	0·7	·32	·14	·00	·55	+0·95	171	36	29	17	18	2·2	—	quartz-dioritic	quartz-diorite
Nh. 99	51·0	42·5	2·0	4·2	0·3	—	·12	·06	·00	·54	+10·5	322	47	8·5	13·5	31	1·4	—	na-rapakiwitic/leuco-quartz-dioritic	leuco-quartz-diorite
L. 103	50·3	41·6	7·0	0·4	0·3	0·4	·31	·16	·00	·47	+8·35	266	39·5	20·5	19·5	20·5	1·5	—	farsunditic/leuco-peléeitic	hornblende-quartz-diorite

* $CaCO_3$ deducted.

J. 154: Hyalo-pantellerite, rare albite phenocrysts in a glassy ground-mass. S.Batu Tatak, tributary of Segama River. Analysis by P. Esenwein.

Nh. 240: Chert-like contact-rock. Bukit Rindian, near Kota Belud, northern part of the west coast. Analysis by J. von Steiger.

Nh. 95: Quartz-diorite. South coast of Kudat Bay, Kudat Peninsula. Analysis by W. Vögtli.

Nh. 99: Leuco-quartz-diorite. South coast of Kudat Bay, Kudat Peninsula. Analysis by W. Vögtli.

L. 103: Hornblende-quartz-diorite. Segama River, 3 km. west of Kuala Telawas. Analysis by W. Vögtli and J. von Steiger.

The Niggli values for the North Borneo ophiolites are set out in Table IX and are reproduced graphically in Figs. 21 to 27.

Both the chemical and the microscopic examinations show that basic to ultra-basic rocks poor in silica greatly predominate. A notable concentration of the analysis values lies in the region from si 107 to 123—that of the principal field of distribution of gabbroid (basaltic) magmas. Most gabbros, the basalts-dolerites, diabases and some spilites of the North Borneo ophiolites fall within this range. Olivine-gabbros, troctolites and peridotite-serpentines depart from this point of concentration with successively diminishing si-values, while the keratophyres and most of the spilites lie in the region of higher si-values (see Fig. 21).

The customary variation diagram arranged according to "si" is, as is well known, capable of only limited application for the representation of ophiolitic rocks. This is due to the fact that the values fm, al and c vary widely between si 50 and 110, according to whether olivine (fm), diallage (fm, c) or basic plagioclase (c, al) predominates in the rock. The plotting of curves of variation is, therefore, of doubtful value. The alkali values alone show a steady and characteristic course. Niggli (in Burri and Niggli, 1945, pp. 180, 181), using Rosenbusch's classification, has utilized the si-alk diagram for the systematization of basaltic rocks. His field boundaries between basalts, sub-basalts and alkali-basalts have been copied in Fig. 21 (lower part). The diagram discloses an interesting subdivision of the ophiolite clan of North Borneo, which is confirmed by a consideration of the analysis data of other Indonesian ophiolites (Fig. 22). Beginning with the types which are poor in silica, the peridotites, serpentines and troctolites to olivine-gabbro fall into the field of the sub-basalts; gabbros, basalts and dolerites lie in the border zone between sub-basalts and basalts; and the spilite-diabases unmistakably in the category of the alkali-basalts. The analcite-diabase H. 59 even, falls in the field of the tephrite-basanites, which lies in the diagram above the alkali basalts. Thus the three chief petrographic groups of the North Borneo ophiolites, i.e. the peridotite-serpentine, the gabbro-basalt and the spilite-diabase groups are also petrochemically characterized as sub-basalts, as transition members between sub-basalts and basalts, and as alkali-basalts.* Consequently the spilites which occur in connection with the peridotite-serpentines, gabbros, dolerites and basalts, form a well-defined group, not only on the basis of their mineral composition and texture, but chemically as well. They are linked, however, by transition members with normal basaltic to sub-basaltic rocks. It may also be pointed out that no North Borneo ophiolites fall in the centre of the basalt field (plagioclase basalts) in the si-alk diagram, but occupy its border area only.

The following data will prove that the Borneo spilites and similar rocks from the Malay Archipelago correspond entirely to the classical British spilites, but that Alpine orogenetic-metamorphic ophiolites of similar chemical composition are also found.

*Fig. 21 shows that the spilitic rocks exhibit higher alk-values than the other members of the Indonesian ophiolites. This confirms Niggli's conclusion (in Burri and Niggli, 1945, bottom of p. 550), but contradicts the findings of Van Overeem (1948, p. 96), who, however, considered a wider si-range.

	si	al	fm	c	alk	k	mg
R. 26 Spilite, North Borneo	123	25·5	43·5	16	15	·02	·45
Spilite, Devonport (Dewey and Flett, 1911)	107	25·5	44·5	17	13	·04	·46
Theralite-diabase, Central Java (Niethammer, 1909)	128	25·5	42·5	18·5	13·5	·11	·51
Lamprophyric rock, Talaud Islands (Roothaan, 1925)	135	25	47·5	13	14·5	·07	·59
Chlorite-schist, P. Cuolm, Grisons (Burri-Niggli, 1945, p. 112)	103	25	46·5	12	16	·29	·47
H. 123 Spilite, trachytic, North Borneo ..	139	24	50·5	11	14·5	·02	·58
Spilitic olivine-diabase, central part, Herefordshire (Blyth in Burri-Niggli, 1945, p. 504)	121	24	51	11·5	13·5	·03	·62
Albite-actinolite-schist Vals, Grisons (Roothaan in Burri-Niggli, 1945, p. 111) ..	133	18·5	56·5	12	13	·06	·72

The magma types ascertained from the molecular values are likewise given in Table IX. In connection with this classification, the spilitic rocks again occupy a special position in relation to the rest of the ophiolites. They belong to the Na series as mugearitic, na-lamprosyenitic, essexite-gabbro-dioritic, theralitic, theralite-gabbroid and melteigitic members, while most of the other ophiolites can be included petrochemically in the calc-alkali series. Consequently, the North Borneo ophiolites represent a natural association of rocks belonging partly to the Pacific and partly to the Atlantic suite. The rocks of the Talaud Islands examined by Roothaan (1925) are also of the same type.

In calculating the molecular values from the chemical analyses of carbonate-bearing spilites, the question arises as to whether the total Ca is to be considered, or whether only that part of it combined with silica (the $CaCO_3$ having first been deducted from the whole) shall be assessed. On reflection, both methods of calculation are seen to be arbitrary. Even if one without deduction for CO_2 is, no doubt, the more correct method here. The composition of rock R. 26 might well correspond with that of the average magmatic melt, and the Ca, now combined with CO_2, though perhaps previously combined with silica, might have arisen from the magmatic melt. The position is different with regard to rock R. 7. The molecular values yielded by chemical analysis correspond well, apart from the somewhat higher si, with those of the melteigitic magma type; those of the carbonate-free rock with those of the theralitic magma type. The question raised cannot be decided in this case by comparison with known magma compositions. But as the c value (30) of the carbonate-bearing rock R. 7 is somewhat high by comparison with that of the other members of the spilite series, it seems that part of the Ca is of external origin.

Before discussing the general chemistry of the ophiolite group of North Borneo, the acid extrusive rocks, of which there were only two samples for

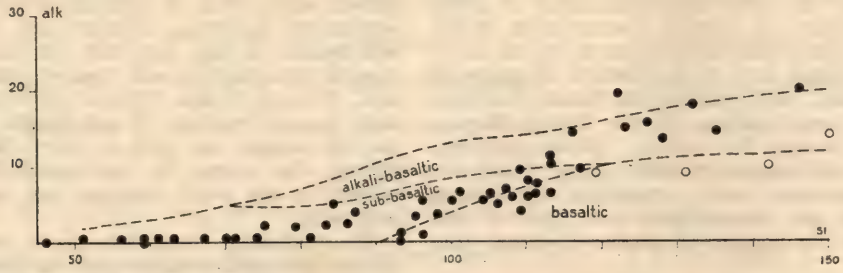


Fig. 22. Alk-si diagram of Indonesian ophiolitic and dioritic rocks

Variation diagram of the Niggli molecular values alk-si for Indonesian ophiolitic rocks (black circles) and of dioritic rocks of unknown association from W. Borneo (hollow circles).

proceeds from the possible, perhaps even probable, but not easily demonstrable, assumption that the total Ca and the CO_2 are magmatic in origin, the question raised above is still unanswered. It may perhaps be true that, by and large, $CaCO_3$ belongs to the ophiolites as an integral magmatic constituent and cannot be considered a foreign ingredient. But this is no longer valid within the limited range of a rock sample or a chemically analysed specimen, for there is no doubt that the $CaCO_3$, as a constituent of high solubility, has migrated, and that the amygdaloidal carbonate is not here a primary constituent. Whether all of it is of outside origin, or only a part, or whether, perhaps, even more has moved away than has come in, it is impossible to judge. Accordingly, it will be as well to calculate the molecular values both before and after deduction of the $CaCO_3$ and then to ascertain from individual cases which values yield the more likely result. For this reason the values are given in Table IX according to both methods of reckoning.

Comparison of the two groups of figures shows that, in the case of R. 26, the rock containing carbonates corresponds closely to the mugearitic magma type, and therefore to a common spilite composition, while the variant calculation made for carbonate-free rock cannot be assigned to any magma type. Calculation analysis, may be mentioned. Acid rocks rich in alkali play an important part in the spilite-keratophyre associations of epi-continental formations; but they seldom occur in the serpentine-gabbro-diabase-spilite series syngenetic with siliceous sediments. The keratophyre St. 189, of bostonitic-pulaskitic composition, fits easily into the association, admittedly by reason of the strongly turbid feldspar with a large surplus of alumina. The hyalo-potash rhyolite (= pantellerite) J. 154, the only rock of this kind collected, falls, on the other hand, mainly within the feldspar triangle Or-Ab-An, rather outside the range of the other ophiolites. But these types of rock are also absent among the Miocene Simporna volcanic rocks. However, according to Roothaan's investigations (1925), analogous k-rich rocks are associated in the Talaud Islands with Na-rich spilites, typically calc-alkalic dolerite-gabbro-peridotites and cherts, a typical ophiolitic association like that of the Borneo Danau Formation. It is thus probable, even if it is not conclusively proved, that the sample J. 154 belongs to the ophiolite clan.

The molecular values of three quartz-diorites from two geologically different occurrences have been included in Table IX and the relevant diagrams. In the outcrop south of Kudat Harbour, which is strongly imbricated and whose geological relationships cannot

be decided, the two analysed quartz-diorites Nh. 95 and Nh. 99 are linked with rocks of the Danau Formation (Enclosure IV). But the hornblende-quartz-diorite L. 103 from the Segama River (Enclosure VIII), corresponding chemically to the Kudat rocks, is associated with hornblende-plagioclase-gneisses and amphibolites, and might belong to the gneiss complex which borders the Danau Formation there, along the line Mensuli-Segama-Telewas. From the purely petrochemical point of view, these three Na-rich rocks fit very well into the field of variation of the ophiolites,

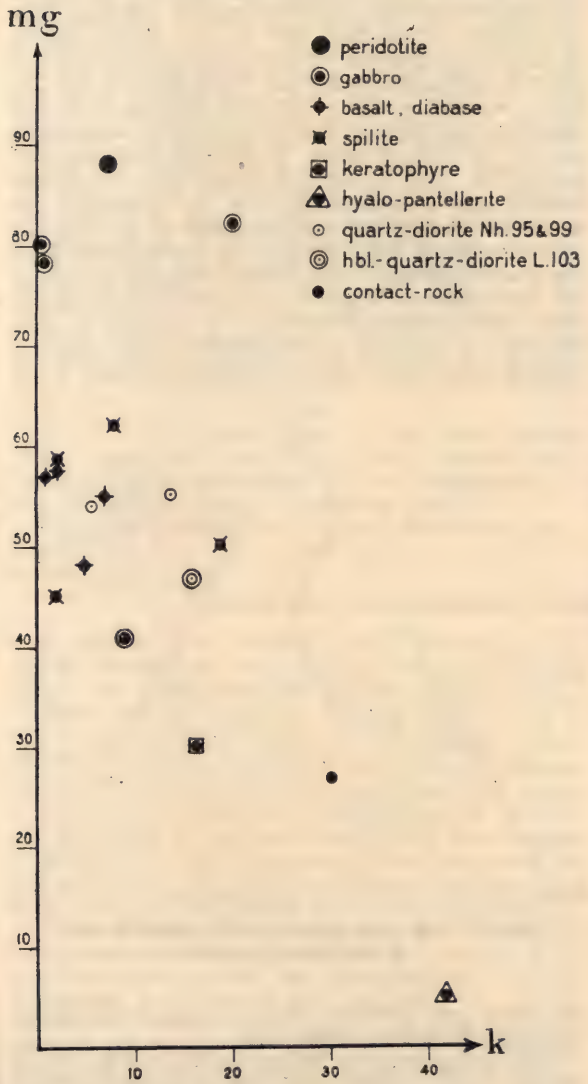


Fig. 23. Mg-k diagram of the ophiolitic suite of the Danau Formation

Diagram of Niggli molecular values mg-k for the ophiolitic suite of the Danau Formation, North Borneo.

$$mg = \frac{MgO}{MgO + FeO} \quad ; \quad k = \frac{K_2O}{K_2O + Na_2O}$$

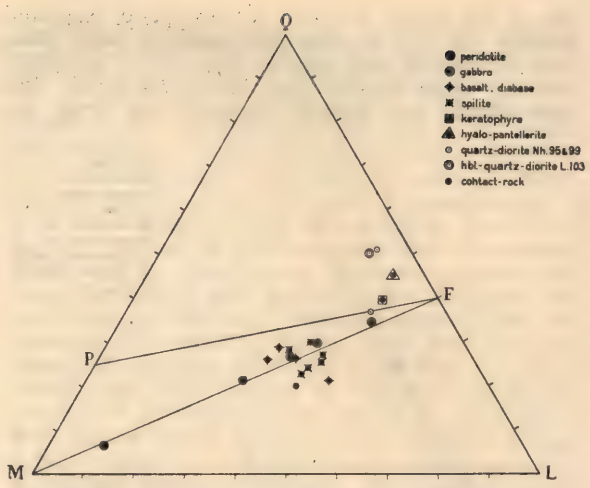


Fig. 24. Q-L-M diagram of the ophiolitic suite of the Danau Formation

For explanation see Fig. 18.

but not into that of the Tertiary, k-rich, igneous rocks of Kinabalu. However, this chemical comparison does not prove that the quartz-diorites belong to the ophiolite clan, for one might expect that the hornblende-plagioclase-gneisses and amphibolites, associated with rock L. 103, but separated by their metamorphism abruptly and without transitions from the Danau ophiolites, would also fall within the range of chemical variation of the ophiolites.

Figs. 21 and 22 are particularly suitable for the study of the general characteristics of the magmatic rocks of the Danau Formation, and for comparison with other ophiolite clans. Fig. 21 demonstrates, as has already been shown, that as si increases, the alk-values also

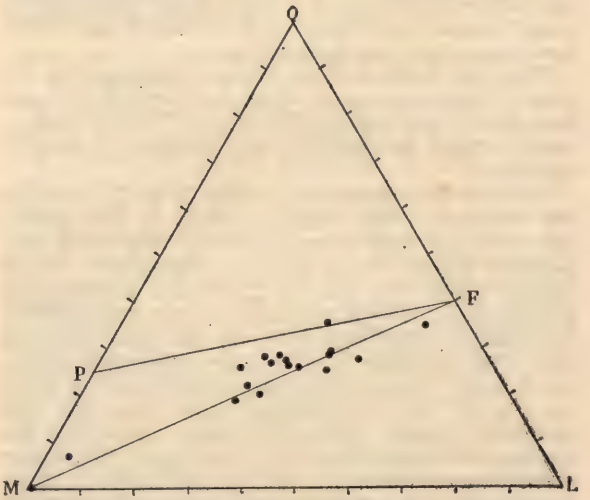


Fig. 25. Q-L-M diagram of the ophiolitic rock suite of the Talaud Islands

For explanation see Fig. 18.

rise, at first slowly, but from 110 onwards by leaps and bounds. In this si-range the transition takes place from sub-basaltic and basaltic rocks of the calc-alkali series to alkali basaltic types of the Na-series. But these Pacific and Atlantic igneous rock types are

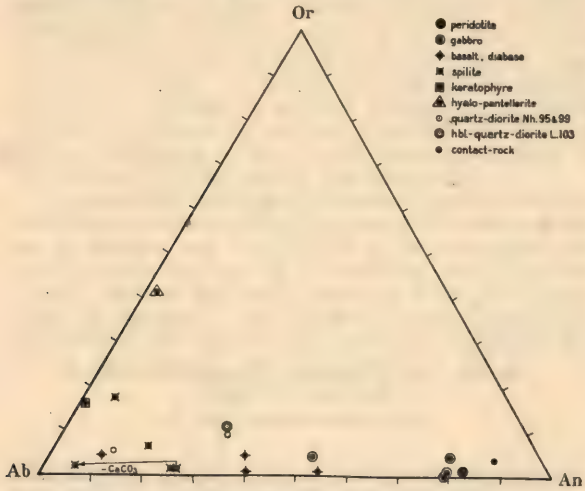


Fig. 26. Or-Ab-An diagram of the ophiolitic suite of the Danau Formation

consanguineous and are linked to each other by transition members.

The presence of faint Atlantic characteristics among rocks of predominantly Pacific type has already been established among the Alpine ophiolites (Burri-Niggli, 1945). Stronger Atlantic influence and a decline in Pacific types at si $>$ 110 distinguish the spilite-rich ophiolite clan of North Borneo and give it the individual character of the province (compare Fig. 22 with Fig. 107 in Burri-Niggli, 1945). Such a transitional position is certainly not unusual; it is also to be found among recent volcanic provinces, as Burri and Niggli (1945) have more than once pointed out.

The k-mg-diagram of the Danau ophiolites (Fig. 23) shows a variation course which is essentially different from that of the intermediate to acid Tertiary igneous rocks of North Borneo (Fig. 16) but which is typical of ophiolites.

The triangular diagrams of Figs. 24 to 27, in which the molecular base (Niggli, 1936a) of the Borneo ophiolites has been recorded, give a remarkably well-balanced picture of the ophiolite association. In the triangle QML (Fig. 24), M. P, F and L represent the composition of olivine, pyroxene, feldspar and nepheline compounds respectively, and Q the free silica remaining after the formation of the above-mentioned silicate compounds. Rocks whose projection points lie above the line PF are oversaturated with silica and bear normative quartz. Projection points below this line correspond to normative quartz-free rocks. This lower field is again divided by the line MF into an upper region saturated with silica and a lower undersaturated region. In Fig. 24 all major types lie below the line PF, and only the rare acid ophiolite types (keratophyre and potash-rhyolite) and the quartz-diorites of doubtful geological position fall within the upper field. All peridotite-gabbro-basalt-diabase-spilites are arranged along the line M (compounds of olivine type) to F (feldspar). In this connection it is especially noteworthy that all the coarse-grained igneous rocks which were analysed (one dunite and four gabbro specimens) lie in a straight line which almost coincides with the line MF. Olivine and plagioclase are major constituents of these rocks, which differ considerably in quantitative mineral content. The development of these rock types with different colour index must obviously have been determined by the crystallization-differentiation of olivine and plagioclase from a gabbroic magma. An analogous development along line MF is also shown in the corresponding diagram of the basic igneous rocks of the Talaud Islands (Roothaan, 1926), given in Fig. 25; here a variability may be observed ranging from pure dunites to anorthosites, the latter occurring, admittedly, only in the form of lenses. Pyroxenites and pyroxene-rich gabbro, both in North Borneo and on the Talaud Islands, play a subordinate role, one essentially less important than in the ophiolite series of the Mediterranean orogenic belt. Besides the peridotite-gabbros, the basalt-dolerites of the Danau Formation also fall in the field situated a little above the line MF in Fig. 24. The spilite-diabases, however, by reason of their content of minerals undersaturated with silica in relation to M and F (chlorite, epidote, analcite), lie for

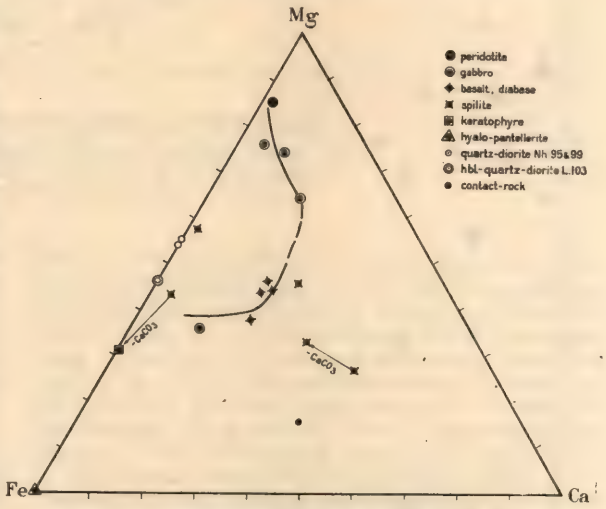


Fig. 27. Mg-Ca-Fe diagram of the ophiolitic suite of the Danau Formation

the most part under the line MF and in the region adjoining the gabbro-basalt field.

This transgression of the projection points into the triangle MFL results from the epithermal mineral content characteristic of spilites, and corresponds to a second differentiation tendency. Such an encroachment on the MFL field by the projection points, which in the ophiolite series so far known are concentrated in the triangle PMF, is not in itself unusual. The tendency is, however, more pronounced among the Indonesian examples cited than among the Alpine-type ophiolites.

This provincial trait is likewise connected with the essential participation of alkali-basaltic-spilitic rocks. Noteworthy points in the QLM triangle of the Borneo ophiolites are that the sediment Nh. 240, which has been metasomatically changed at the ophiolite contact, fits in well in the field of variation of the magmatic rocks, and that the normative quartz-bearing rocks begin to diverge from the quartz-free types when their feldspar content is high; they cross the line PF when L = 49.

The feldspar triangle Or-Ab-An of the North Borneo ophiolites (cf. Fig. 26) likewise clearly expresses the self-contained uniform character of the whole clan. With the exception of sample J. 154 already referred to, which is an isolated occurrence, all the rocks analysed are characterized by a very low Or-content. The projection points occupy the belt bounded by the side Ab-An of the triangle and the line passing from the corner Ab toward the point k = 0·20. Proceeding from An to Ab, this narrow band may be subdivided into peridotite, gabbro, basalt-dolerites, diabases and spilites; Pacific rocks merge gradually into Atlantic. This diagram shows much analogy with that of the Alpine ophiolites (Burri-Niggli, 1945, Fig. 61). The only difference is the field's expansion, caused by the spilites, toward the point Ab. In Fig. 26 again, the chert-like altered sediment Nh. 240, similar in composition to epidote or pumpellyite, falls within the field of variation of the ophiolites.

The ophiolitic rocks occupy, in the mafic triangle (Fig. 27) as well, a uniform, curved variation-band, whose course is determined by the crystallization of olivine, diallage, uralite, chlorite and epidote.

Thus, the ophiolite clan of North Borneo is seen to be chemically quite comparable with known ophiolite associations, but exhibits a provincial peculiarity in the abundant participation of diabasic and spilitic rocks of the Na-series, and in the absence of leuco-gabbroic-dioritic rocks of the calc-alkali series. A spilitic differentiation is linked with the peridotitic, gabbroic, anorthosite-gabbroid differentiation which, however, did not lead to copious formation of keratophyres. It is an open question which rock group is the older of the two. According to Molengraaff (1900), Koolhoven (1935) and to observations made by various other Dutch geologists and published by Zeijlmans van Emmichoven (1939) and Van Bemmelen (1939), the diabase-spilite rocks in central, west and south-east Borneo are certainly older than the gabbros. In North Borneo also, in the area of the tributaries Malua and Sangitan of the Kinabatangan river basin, according to Wenk's observations, the spilitic rocks, locally developed as pillow-lavas and associated with radiolarites, are cut by younger gabbro intrusions. The question of the relative age of the serpentines and peridotites, however, has not been settled.

Thus, it appears that at the beginning of the ophiolitic cycle the magma exhibited an alkali-basaltic composition and was rich in volatile constituents. Yet the age relationships, in particular those concerning the serpentine and peridotite rocks, have still to be clarified.

We may add that the chert-like rock Nh. 240, which, judging from its occurrence and appearance, certainly represents a sediment modified at the ophiolite contact, is so highly similar to the ophiolites in its chemical composition that its projection point falls, in almost all the diagrams, in the ophiolite field. Nevertheless, the rock does not correspond to any type of magma.

Endomorphic and Exomorphic Contact-Metasomatic Alteration Products

In describing the sediments and ophiolites of the Danau Formation, reference has occasionally been made to recrystallization manifestations, mineral replacements and formation of new minerals, all of which owe their formation to post-volcanic hydrothermal processes. The processes concerned are such as silicification, calcification, ore-impregnation, chloritization, epidotization and prehnitization of both the ophiolites and the sediments harbouring them, besides albitization (adinole formation) which encroaches on the sediments. The texture and mineral content of the rocks to be described below prove them to be recrystallized and remineralized ophiolites and sediments. Metasomatic processes have played an essential, if not exclusive, part in them. The metasomatites are almost permanent associates of the ophiolites, viz. of the serpentines, diabases and spilites. Judging from the samples on hand, they seem to occur particularly frequently in the southern coastal strip of Kudat Harbour. Their wide distribution is a consequence of the high water and carbonic acid content of the ophiolitic residual solutions. It might also be connected with the subaquatic extrusion of the ophiolitic magmas in sediments impregnated with water and not yet consolidated. The following descriptions are based on an examination of 104 samples and 75 thin sections. These do not, for the most part, belong to large homogeneous rock masses, but are local mineral assemblages alternating in quick succession, as is to be expected from such a mode of origin.

Re-crystallized radiolarian cherts and sandstones, chalcedonites

Re-crystallization manifestations have already been spoken of in describing the radiolarian cherts. Figs. 1 and 2, Plate VI, show a radiolarite in which only the radiolaria are chalcedonized, whereas it is evident from Figs. 3 and 4 that the whole rock has experienced complete re-crystallization. Despite the intensive neoformation of quartz, the contours of the radiolaria are still very plainly recognizable in ordinary polarized light (Fig. 3). They disappear, however, if the analyser is introduced (Fig. 4). The re-crystallized radiolarian cherts can readily be recognized megascopically by their greasy lustre. The original red colouring of the radiolarites has been succeeded by greyish-brown. In thin section one can see that the limonitic and haematitic diffuse pigment of the chert has coagulated on re-crystallization into brownish-black shreds. A vein-like penetration of chalcedony stringers often goes hand in hand with the re-crystallization, and thus the cherts may be broken up into fragments floating in a chalcedony network. As has already been mentioned, these breccias are strongly similar in appearance to the

so-called ring or cockscomb ores. Fig. 2, Plate VII, depicts a section of a chalcedony vein.

Reference has likewise already been made to re-crystallization manifestations in sandstones. They are recognizable as zones of growth around quartz grains. Figs. 3 and 4, Plate 1, show a thin section of a re-crystallized sandstone with foraminiferal residues. The remains of strongly corroded limestone shells, disintegrated into single grains, float in quartz grains without having been displaced from their original position.

Silico-Carbonate Rocks

Siliceous limestones

Where marl and marly limestones occur in the beds overlying the radiolarian cherts, a narrow transition zone generally occurs in which siliceous and marly portions are interbedded in thin bands and lenses. Reichel (see Appendix III) considers these rocks as silicified limestones. We believe rather that the alternation is due to primary interbedding. A movement of material, at any rate on a small scale, must certainly have taken place where the siliceous radiolarian shells embedded in limestone ooze have been replaced by calcite pseudomorphs, and where the calcite shells of *globigerina*, lying in siliceous ooze, have been replaced by quartz-chalcedony pseudomorphs, but where re-crystallization has otherwise not set in. Consequently, these siliceous limestones seem to represent sediments which are still almost unchanged.

Silicified limestones

In other cases, the silicification of limestones is much more conspicuous. The quartz, in the shape of polygonal or, more infrequently, denticulate grains usually peppered with fine calcite dust, especially in the nuclei, replaces the carbonate, which is still preserved in nests or surrounds the quartz-lenses in small-grained " meanders ". Limpid chequered albite is a rare minor constituent. Fossil remains are still preserved in a strongly silicified limestone (Nh. 386). The limestone frameworks of *lepidocyclina* (of the group *L. sumatrensis* according to Prof. Reichel) and *lithothamnia*, are disintegrated into tiny granules embedded in quartz, in a manner rather similar to that obtaining in the sandstone, a section of which is illustrated in Figs. 3 and 4, Plate I.

Calcified cherts

Red pigmented fragments of cryptocrystalline cherts are penetrated by veins of coarsely spathic calcite with sporadic dolomite and barytes. The carbonate may also penetrate and replace the chert, giving rise to a fungus-like formation, and the cherts may be re-crystallized. In these more strongly re-crystallized cherts, ore granules and clusters of sericite-chlorite scales arise as further constituents.

Quartz-carbonate metasomatites

Whereas in the examples dealt with so far the original rock has still been identifiable despite re-crystallization, this no longer applies to those that follow.

The samples are medium to coarse-grained spathic, usually mottled greyish-green and red, but occasionally uniformly grey. They are occasionally interpenetrated by a white calcite network. In appearance they are not to be distinguished from ophicalcites and the similarity persists even in thin section. We seem to recognize here and there the phantom of a diallage or olivine crystal, and it is quite possible that we are dealing with extremely calcified and silicified ophiolites of the peridotite group. For the rest, the thin sections are extraordinarily varied. The sulcate and lobate grains of calcite and quartz are usually powdered with ore, and calcite globules occur in the quartz. They may be so densely concentrated that a gradual transition from quartz to calcite takes place. Pipes with plug-texture, star-like groupings and pinnate proliferations, resembling palm-fronds, of calcite or quartz, diversify the picture in the thin sections. The proportion of calcite to quartz is very variable; calcite may occur as almost the sole constituent. In such cases the rock is uniformly grey and in sample is marble-like. Serpentine, chlorite and chromite occur as accessory constituents.

Metasomatized Ophiolites

Calcified and silicified serpentines

The appearance of the remineralized serpentines differs greatly according to the degree and type of metasomatism undergone. Where alteration is not far advanced, the rocks are still serpentine-like in appearance; where the serpentine has been more considerably or totally replaced by carbonate and (or) quartz, the rocks appear mottled to brecciated.

In the case of wehrlite-serpentine, the diallage at first falls prey to a silicification or calcification through separation of chlorite. In addition, quartz and calcite occur in hair-like cracks. When alteration is more advanced, the serpentine also becomes impregnated with opal, quartz in fine scales, and calcite. The serpentine can also be wholly replaced by ore-powdered calcite and quartz. In spite of this radical metasomatism, the serpentine texture may be completely preserved, as Fig. 4, Plate VII, shows; the picture entirely alters, it is true, on introduction of the analyser (Fig. 5, Plate VII). The chemically highly resistant spinels and chromite, characteristic accessories of serpentines, remain unchanged.

Ophicalcites

Megascopically, the ophicalcites are indistinguishable from the quartz-carbonate metasomatites. Like the latter, the ophicalcites are in general pronouncedly coarse spathic, speckled with grey, green and reddish tints and frequently interwoven with a white network of calcite. The thin sections are also very similar, apart

from more abundant serpentine in nests and stringers. Grains of chromite and picotite are almost constant accessories, barytes occurs only rarely. The ophicalcites are very widespread in the Blantian River area.

The quartz-carbonate-metasomatites and the calcified and silicified serpentines are probably closely related genetically, and represent various degrees of silicification and calcification.

Calcified gabbro

Whereas calcified serpentines are widespread, gabbroid rocks appear less susceptible to metasomatic remineralization. In a troctolite whose olivine is completely replaced by a fine-scaled felt of yellowish, greenish and bluish serpentine, bowlingite and chlorite, with much skeletal titaniferous iron, concretionary proliferations of calcite invade not only this felt but also the otherwise quite fresh plagioclase. The plagioclase is almost pure albite (0% to 8% An). The abundance of small apatite needles, as inclusions in the plagioclase and in the serpentine-chlorite felt, is striking.

In one gabbro-diabase the mafic minerals have been replaced by a greenish-yellow, almost isotropic mass, which fills the interstices between the plagioclase laths. The feldspar is turbid although, exceptionally, in small cracks and in the narrow marginal zones, it is limpid. Here also it is extremely rich in albite; determinations revealed an An content of 1% to 5% or, exceptionally, 15%.

Calcified diabases

Diabases interspersed with carbonate occur more frequently than remineralized gabbros. In appearance they are indistinguishable from the unmodified diabases; the carbonate content is observable only in thin sections. The carbonate occurs either in grains evenly distributed in the rock or in proliferations and in cracks. It may replace either the mafic minerals or the plagioclase. Where mafics have been preserved they are found as arborescent augite; where the plagioclase is still present and not too strongly turbid it is again rich in albite. Epidote occurs at times very plentifully in the calcified diabases. The carbonate is mainly calcite; in one case it is breunnerite, the grains of which are bordered with a fine rim of limonite.

Remineralized spilites

Each of the three samples to hand shows individual characteristics. In a vitro-porphyritic spilite (from Tanjong Bangau, west coast of Kudat Peninsula), the texture of which has been preserved undamaged, the plagioclase phenocrysts are completely altered into a mixture of analcite and chlorite. The greyish-brown, ore-dusted glassy groundmass, with still fresh arborescent augite microlites showing arcuate extinction, is strongly decomposed and permeated by calcite and zeolites.

The two other samples come from Ruby Island, an islet lying off the east coast of the island of Banggi (cf. Enclosure III). One sample is dark reddish-brown, finely-microlitic to aphanitic, with haematite-coated slickensides. The intersertal texture appears unaltered in the thin section, but the little laths of plagioclase and fans of augite have been entirely replaced by an extremely fine felt-like fabric of an indeterminable colourless mineral exhibiting medium-high double-refraction. The ground-mass consists of limonite with haematite crystal skeletons.

The other sample is light greenish-grey, weakly brecciated, with calcite, zeolites and epidote in nests and along small cracks. The microtexture shows only weak affinity with that of the spilites. Turbid plagioclase phenocrysts up to half a millimetre in size, often in glomero-porphyritic groups, lie in a ground-mass impregnated with albite and interlaced with small scales of chlorite, leucoxene dust, small grains of epidote and a few tiny albite needles.

Calcified breccias and tuffs

The greyish-green or dark-violet rocks are diabase-like or brecciated in appearance. The hydrothermal solutions were easily able to circulate in them, and on this account metasomatically altered breccias and tuffs are widely disseminated rocks.

The thin sections are highly diversified. Only a few characteristic traits will be mentioned here. The spilites predominate among the components of both the breccias and the lithic tuffs; serpentine, diabase and chert fragments occur less often. They are, apart from the serpentine, seldom fresh, often completely replaced by an almost isotropic cryptocrystalline mineral aggregate, without having lost the typical spilitic texture. The fragments lie in a cement of calcite dusted with ore, containing grass-green or bluish-green pennine in spherulites or in concentric pennine-calcite oolites. Leucoxene is always present in abundance, albite grains occur locally in the cement. The rock fragments may also be partly or wholly limonitized. Where the calcite occurs in veins it assumes a shelly-concretionary form, and the calcite shells are then often separated by " meander-like " limonite stringers. Quartz is usually present in a few lobate grains corroded by carbonate. One spilite tuff is very strongly impregnated with epidote in radiating fibrous pockets, and to a lesser extent with albite, chlorite and quartz. Brown-dusted prehnite occurs in proliferations.

Schalstein

A group of rocks was separated from the calcified tuffs and breccias described in the preceding section; their tuffaceous nature has, in part, been plainly preserved, but is also, in some cases, questionable. They have suffered a re-mineralization other than that of the predominantly calcified tuffs and breccias. They will be designated here as " schalstein ". No well-defined boundary exists between the schalstein and the calcified tuffs; they merge into one another. Carbonate is found occasionally in the schalstein as well, but usually in small quantities only. Albitization is more evident, sometimes in the form of chequered albite. Chlorite, epidote-clinozoisite, titaniferous minerals, usually titanite, less often rutile and ore, are always

present in varying amounts. Bluish-green hornblende, prehnite, sericite, quartz and apatite may be associated with them. The schalsteins are predominantly green, more rarely grey, aphanitic, massive or arenaceous and finely laminated; the structure is occasionally weakly brecciated.

Metasomatized Sediments

Adinole-schists

No genuine adinoles resembling cherts in appearance are present in the collected rock material. On the other hand, judging by the samples available, albitized clay, slates and fine-grained tuffites seem to occur at the ophiolite contact. The green, grey, brownish-violet or yellowish-brownish compact, at times splintery, rocks show a more or less strongly pronounced schistosity. The rocks of this group are fine-grained throughout. The diameter of the mineral components usually varies between 0·01 mm. and 0·1 mm.; only a few grains may attain a size of 1 mm. Besides rocks consisting almost exclusively of albite and quartz, varieties are also found which are very rich in chlorite. Calcite is also a frequently occurring constituent, small grains of magnetite and titanite are seldom absent, while clinozoisite-epidote appears occasionally and sericite rather more often.

Spilosites

A few samples of grey spilosites are available, which splinter on fracturing. These were collected by Niethammer from an ophiolite contact 2½ km. east of Kotà Belud. Another spilosite locality is situated some 20 km. farther to the NE., where the rock occurs again along with ophiolites. In one of the samples, tiny dark nodules are readily visible to the naked eye in the light violet-grey compact rock; in the others, the nodular development is only observable in thin section. One such example is shown in Fig. 3, Plate VII. The nodules, approximately 0·1 mm. in size, show the finest aggregate polarization; they appear to consist of a mixture of quartz and feldspar; they are embedded in a cryptocrystalline mass which is darker in hue owing to the carbonaceous pigment concentrated around the nodules. The whole rock is interspersed with specks of sericite, which may on occasion occupy about a third of its volume. In another spilosite the nodules consist of uniform, untwinned albite grains which, particularly at the nucleus, are thickly studded with microlites of sericite and biotite, and with graphitic dust. The spherical albite nodules, approximately 0·1 mm. in size, lie embedded in a sericite ground-mass. In another sample the nodules consist of greenish chlorite scales, embedded in a fine felt of sericite, quartz and feldspar; quartz and calcite occur in little veins and nests. The sample comes from a diabase contact. In one specimen, calcified and albitized diabase is present in contact with spilosite.

Chert-like contact rock

One rock sample (Nh. 240), of doubtful mineral composition, which Niethammer collected approximately 9 km. upstream from Kota Belud on Bt. Rindian, would seem from its outward appearance to be a radiolarian chert. It occurs in the interstices between pillows of a strongly epidotized spilitic pillow-lava. The rock is of resinous appearance, aphanitic, fractures conchoidally, and is violet-brown in general colour, although greenish in parts. Its hardness is a trifle less than that of chert; in lustre it is somewhat duller. The weight seems decidedly too great for a chert. Determination of the specific gravity yielded the value of 3·20, which is improbably high for a siliceous rock. Accordingly a thin section was prepared, which revealed that no siliceous rock was present. In a limonite-impregnated mass with extremely fine aggregate polarization, somewhat lighter pockets up to 0·2 mm. in size and of finely-acicular texture are distinguishable. The crystals are so tiny as to be no longer identifiable optically. They might conceivably be clinozoisite-epidote or pumpellyite. X-ray powder photographs yielded lines which, however, could not be identified with either of these two or with any other known mineral. The rock was analysed and revealed the following values:

Nh. 240: *Chert-like contact-rock*

SiO_2	33·57	Between the pillows of an epdotized spilitic pillow-lava. S. end of Bukit Rindian on the S.Wariu, 9 km. SE. of Kota Belud.
TiO_2	0·55	
Al_2O_3	21·49	
Fe_2O_3	11·62	
FeO	1·65	
CaO	20·46	
MgO	2·51	
MnO	0·24	
Na_2O	0·66	
K_2O	0·43	
H_2O-	0·36	
H_2O+	6·51	
P_2O_5	0·08	
CO_2	none	
Total	100·13	
Sp. gr.	3·20	

Analyst: J. von Steiger.

Apart from somewhat too low silica and too high water content, the total composition of the rock agrees quite well with that of certain epidotes and of pumpellyite. But that still says nothing about the nature of the parent rock.

There is no doubt that the sample in question is a sedimentary rock re-mineralized at the spilite contact. The kind of sediment remains uncertain, as no clues are available to enable us to establish how far the original chemical composition was metasomatically changed. Assuming the parent rock to have been a marl, it would chiefly have been a matter of decalcification. But the sample may also represent a radiolarian chert, radically replaced metasomatically by a fine aggregate of epidote or pumpellyite. In the chapter on the petrochemical characterization of the ophiolites it was pointed out that the chemical composition of this metasomatically altered sediment closely approaches that of the ophiolites.

ORE-MINERALIZATION

Most, if not all, of the ore occurrences known so far are connected with the ophiolites, and it seems indubitable that they came into existence following upon the ophiolite intrusions.

The country has been explored for ore deposits, particularly by prospectors with little geological training. The exertions of these explorers harvested no practical results, nor did they extend our knowledge of the geological conditions of the ore deposits. An exception was the young chemist and geologist Frank Hatton (1885), who unfortunately, after only 18 months of research activity, met an untimely death through an accident on the Segama in 1883.

We are indebted to Pilz (1913) for a good general view of the geological conditions of the country and its mineral deposits. The following details have been taken in part from his work.

In describing the serpentine and peridotites, mention has been made of their often being accessorily *chromite*-bearing. The chromite is accumulated in placers in the sands of rivers flowing through large peridotite outcrops. Such chromite placers have been detected on the shore of Marudu Bay and on the north coast of Banggi Island. Assaying of the chromite sand for precious metals has always revealed, according to Pilz (1913, p. 36) quite a small quantity of gold and an insignificant platinum content. A lens of chrome iron ore of inferior quality occurs, according to Pilz, in the pyroxene-bearing serpentine in the neighbourhood of Paranchangan village on the upper Sugut. Hotz has collected massive chromite ore (H. 24) from a dunite on the southern coast of the island of Manawali (cf. Enclosure III).

It has already been stated that secular weathering of the peridotites has caused local formation of *pisolitic limonites*. *Iron-rich laterites* are common, as a weathering product of peridotitic rocks. Limonitized spilites with small, well-preserved rods of albite, and little augite pinnae completely altered into limonite, also occur among the contact-metasomatic formations.

The radiolarian cherts of North Borneo, as in countless other places, often contain manganese. The oxidic *manganese ores* (psilomelane) frequently form thin coatings along cracks or the joints of bedded rocks, and less frequently form lenses of compact ore. They also often occur interbedded with thinly stratified radiolarian cherts. The manganese ore occurrences of Taritipan on the SE. coast of Marudu Bay (cf. Enclosure V) gave rise at one time to a short-lived, audaciously planned attempt at exploitation, and reports of their alleged fantastic richness appeared even in technical journals (Dieseldorff, 1906). Pilz (1914) has stated that the details concerning the quantity and quality of the ore were derived from reports which were later proved to be incorrect. Owen Rutter (1922) has given a dramatic picture of the brief episode of manganese ore mining (op. cit. pp. 284, 285).

Among the rock samples which Hotz collected from that locality is a piece of psilomelane with a crust of radially-fibrous inesite. The pale, violet-red crystals are up to 10 mm. in length and 1 mm. in thickness. Dr. Grütter has examined the sample more closely and has established the following properties:

The mineral exhibits two very good cleavages: that along (010) lying approximately normally to the acute bisectrix, extinction $n_\gamma' \wedge c = 58°$; the other cleavage flakes (100) showing an oblique axial emergence and extinction $n_\gamma' \wedge c = 11°–12°$. The axial angle was determined on the Fedoroff Stage; $-2V$ fluctuates between 57°–72°. Determination of the indices of refraction with immersion liquids yielded for $n_\alpha \sim 1{\cdot}616$, $n_\beta \sim 1{\cdot}639$, $n_\gamma \sim 1{\cdot}650$. The axial angle calculated from these values yields $-2V = 69°$. The mineral is decomposed by HCl. Mn, Ca and H_2O were qualitatively proven. The mineral is easily fusible and the hardness was determined as $\sim 5{\cdot}5$. Calcite is the only accompanying material. These properties correspond very well with those specified by Glass and Schaller (1939) for the inesite from Quinault, Washington.

The radiolarian chert and ophiolite outcrops $2\frac{1}{2}$ km. east of Kota Belud contain pockets of wad and pyrolusite; and cherts rich in iron and manganese oxides occur in the upper Bongon River, which runs into the southern end of Marudu Bay. Finally, manganese-bearing radiolarian cherts occur on Banggi Island, whence Hotz has collected samples. So it appears from this that the ophiolite-chert outcrops of the region from Banggi across the east coast of Marudu Bay down to Kota Belud differ from the rest of those in North Borneo in possessing a certain content of manganese. But it should be pointed out that these manganese deposits are poor, and economically unworkable.

The experts do not agree as to the origin of these manganese accumulations. Molengraaff regards the radiolarian cherts of Dutch Borneo as deep-sea sediments. He compares them with the radiolarian ooze, and sees in the presence of manganese ores a confirmation of his view, as manganese nodules likewise occur in the deep-sea deposits. Pilz (1914) supports this view. We are more inclined to assume that the manganese and iron content of the cherts must be related to the ophiolite intrusions.

The few occurrences of *sulphide ores* are also connected with ophiolites and their associated rocks. Prospecting was carried out without result on the gabbroid rocks of the River Karang, a small tributary of the River Karamuak, which flows into the Milian (Kinabatangan) from the north. These rocks are impregnated with copper-bearing pyrites and exhibit marked hydrothermal alteration. Pilz (1914) examined the deposits more closely and briefly described them. Spilitic-diabasic breccias impregnated with pyrites and zinc blende led to equally fruitless prospecting at Pingang-Pingang, on the east coast of Marudu Bay (Enclosure V). Insignificant occurrences of pyrites and chalcopyrite, more rarely of arsenopyrite, pyrrhotite and zinc blende with quartz gangue, appear in different places in ophiolites, and particularly in diabases, or in contact-rocks. These are again impregnations not economically workable.

Occurrences of placer gold seem to be limited to the area bordering Darvel Bay to the north and west (south-east coast of North Borneo). Posewitz (1898) and Pilz (1914) have briefly reported on it and we rely on their information. Alluvial gold was discovered in the Segama in 1883 by a Government officer named Beeston. Some years later the gold deposits were examined and appraised by S. B. J. Skertchley (Report on the Segama Gold Field, 1889, British North Borneo Co., 1897). The sands of this river are everywhere auriferous, although in varying degree, from approximately the mouth of the Telewas up to beyond its confluence with the Bole Besar (cf. Enclosure VIII). Of the tributaries flowing into the Segama, only those on the right bank are gold-bearing, those on the left being sterile. Stamm (in Wanner, 1921) has found a quartz vein in gneiss in the Bole Besar, which contained, besides iron pyrites, traces of gold. Placer gold is also said to have been found in the sands of the drainage areas of the Diwata and the Subahan, and in Pleistocene conglomerates from the Tabanak at Lahad Datu. The quantity of gold must have been everywhere extremely small. It appears mainly in the form of tiny flakes, and only seldom in larger nuggets. In the Subahan one such nugget of 27 gr. was found, the heaviest ever obtained from these placers.

In 1893, more than 100 gold-washers were at work on the Subahan, producing gold to a daily value of three shillings and sixpence to seven shillings per head. But output seems to have speedily declined, for shortly afterwards all gold-washers ceased work, having already experienced disappointment in previous years on the Segama.

Pilz, who examined the alluvial gold deposits, was unable to come to a definite conclusion regarding the origin of the gold. He considers it very probable, however, that it originated from the pyrites of the ophiolites, in particular from the diabases. Gold, though only in faint traces, was identified by him in a pyrites-bearing diabase from the Subahan River. Stamm's findings, however, would suggest that the gold may possibly have its origin in the old crystalline rocks.

A concise historical survey of the discovery of useful minerals is to be found in Worth (1940). The author's material is based to a large extent on old reports made for the British North Borneo Co. Worth also mentions ore deposits and diamond discoveries which we have left out of consideration as they have not been confirmed by later geological investigation.

METAMORPHIC OPHIOLITES FROM THE CONTACT ZONE OF THE KINABALU QUARTZ-MONZONITE

Wenk collected samples in the form of loose blocks of a dark-grey, splintery, brecciated rock in the upper Kadamayan, the source of the Tampasuk, on the south-west slope of Kinabalu (cf. Enclosure VI). Although these samples were not taken from the bed-rock, it can hardly be doubted that they originate from the contact zone of the quartz-monzonite stock. Angular fragments, as big as eggs, of a compact to finely microlitic grey rock, lie included in a rather more coarsely-crystalline, dark greenish-grey cement.

In thin section, the four samples examined (Wk. 81, 82, 87, 89) present a very similar picture (Fig. 4, Plate XIII). The rocks concerned are monomict spilite-breccias. The spilite fragments show a finely microlitic texture. Fine needles of albite lie in a greyish-brown, almost opaque, cryptocrystalline groundmass. Some albite phenocrysts up to 5 mm. in size are partly altered into scapolite, chlorite and calcite. No augite microlites are present, having obviously succumbed to auto-metamorphism towards the end of the consolidation of

the ophiolites and before the rocks underwent contact-metamorphism. In one spilite fragment there is a rounded augite grain which has been altered for the most part into mottled, greyish-green and colourless uralite. Some spilite fragments are impregnated with a hornblende felt and penetrated by hair-like cracks filled with greenish-blue hornblende needles and calcite. Where the spilite fragments show amygdaloidal structure, the amygdules are filled with a fine felt of bluish-green hornblende. Apart from the freshly-formed uralite, the spilite fragments show no contact-metamorphism. With the cement the case is quite otherwise: examination of the non-metamorphic spilite breccias has shown that it consists of a fine mixture of chlorite, albite and possibly calcite; here the cement has been subjected to thoroughgoing re-mineralization. Flasers of bluish-green and colourless hornblende flow around the spilite fragments. The two hornblendes frequently exhibit parallel growth, or form zoned grains, frequently with clouds of leucoxene dust. The following properties have been observed for the pleochroic hornblende: n_γ bluish-green, n_β green, n_α pale yellow, $n_\gamma - n_\alpha = 0{\cdot}026$. Nests of calcite, pennine, limpid albite and grains of pyrrhotite appear occasionally in these hornblende flasers.

A sample (H. 124) from a loose block, collected by Hotz, comes from about the same locality as Wenk's metamorphic spilites. The dark, greyish-green rock is splintery and aphanitic. In thin section it appears as a microlitic, nematoblastic mixture of bluish-green hornblende (approx. 60% by volume, n_γ bluish-green, n_β green, n_α light yellow, $n_\gamma - n_\alpha = 0{\cdot}023 - 0{\cdot}025$, $n_\gamma \wedge c = 15°–17°$, $+2V \sim 80°$), plagioclase (25% by volume, oligoclase-albite, by refraction) and leucoxene (15%). A few amygdules up to 2 mm. in size are filled with a criss-cross of reed-like laths of bluish-green hornblende and impregnated with calcite. This is apparently a sample of a contact-metamorphic spilite.

On the southern ridge of Kinabalu, near the summit, a peridotite lens is in contact with the granodiorite, which also occurs in the former as an apophysis (cf. Enclosure VI). Several samples of this peridotite outcrop were examined (H. 131, 132, 134, Wk. 74). The rocks are throughout very rich in olivine. In one dunite, besides ore-dusted olivine grains, actinolite needles and chromite grains, occurring only sporadically, are discernible. Colourless actinolite appears in the other samples in larger quantities and in the form of fascicular aggregates. Larger plates of orthorhombic pyroxene are also present in one sample ($+2V = 70°–90°$, $n_\gamma - n_\alpha = 0{\cdot}010$). Diopside, colourless chlorite, talc and green spinel occur as accessories. Smallness of grain (0·03–0·5 mm.) characterizes all the samples; the plates of orthorhombic pyroxene alone may attain 3 mm. in size. Points worth mentioning are the usually strongly pronounced cataclase and the complete absence of serpentine, which is always in evidence in all the other Danau peridotites, sometimes abundantly. It is quite possible that the typical peculiarities of these peridotite occurrences—diminution in size of grain, disappearance of serpentine—may be attributed to the contact action of the granodiorites. The rock samples available, however, are hardly sufficient to enable a definite conclusion to be drawn.

Microgranodiorite dykes occur in the Danau Formation on the eastern slope of Kinabalu, in the head-waters of the Sugut and particularly in the upper course of the Makadu (cf. Enclosure VI). The ophiolites are here almost exclusively represented by serpentine, with irregular lenticular lumps of jadeite and nephrite. No peculiarities could be observed which might be attributed to contact influence by the microgranodiorite apophyses.

TECTONICS, GENESIS AND AGE OF THE DANAU FORMATION

All field geologists who have had the opportunity of observing the Danau Formation on their expeditions agree that it is always extraordinarily strongly disturbed. Both Hotz and Niethammer, who have explored the western part of the country and the area running northwards into the two peninsulas of Kudat and Bengkoka, as well as the islands off the north coast, state that both the ophiolites and the sediments accompanying them form isoclinal folds. Hotz describes overturned isoclinal folds on Banggi Island, in which ophiolites, radiolarian cherts, limestones, sandstones and shales are imbricated.

According to Schneeberger the outcrops of the Danau Formation are often bounded by fault systems (cf. Enclosure III). Wenk and Roothaan have established the presence of the Danau Formation in the basin of the River Kuamut, the largest right-bank tributary of the Milian-Kinabatangan: " a very strongly disturbed alternation of quartzites, sandstones and limestones, with ophiolites—basalts, variolites, tuffs and tuff-breccias—and with injected gneisses. Some of the sedimentary components may be imbricated Tertiary ".

Stamm and Jezler have met with similar conditions in the Segama and in the coastal area of Darvel Bay.

The cross-sections of Fig. 3 afford a certain insight into the strongly folded areas, in part compressed into isoclinal folds and crossed by faults, in which the Danau Formation occurs. But they exhibit the conditions only in a highly simplified and schematized form. In reality the complications are so great that they could only be represented by using a much larger scale; but such detailed illustrative material is not available. The geologists had, of course, the task of exploring the country for possible oil deposits. As no interest from this point of view attaches to the areas of Danau Formation, they received only cursory attention. We may also mention, as an additional unfavourable circumstance, that the nature of many

rocks forming part of the Danau Formation cannot be accurately ascertained on the spot, an exhaustive microscopic examination being required for that purpose. In addition, a knowledge of the age relationships of the sedimentary rocks folded with the ophiolites is a prerequisite for the elucidation of the tectonics. But in this case we have only the most elementary data to go upon.

The river basins of the Segama and the Darvel Bay region, investigated by Stamm and Jezler, provide good cross-sections through typically developed Danau Formation. The latter is also particularly well exposed in the valley of the Blantian and its tributaries. The map (Enclosure X) gives only a purely schematized picture of the various rock occurrences; no attempt has been made to portray the tectonics. The different ophiolitic rocks have been kneaded so thoroughly with radiolarian cherts, flysch-like sandstones and shales (cf. Fig. 28), to form giant breccias intersected in all directions by slickensides, that one cannot help wondering whether overthrusts on a large scale were not concerned here. It appears to be quite out of the question that such an intermixture of rocks could arise through autochthonous folding. The question as to whether nappe structure must be assumed in certain regions of North Borneo has been answered in the affirmative by Hotz in his unpublished reports, Stamm (in Wanner, 1921) and Reinhard (1924). Wanner (1921), a well-known authority on East Indian geology and critical editor of Stamm's notes and collections, remarks that Stamm's discoveries yield no definite evidence for nappe structure and that therefore, in his opinion, no grounds as yet exist for acceptance of Stamm's theory. Today we are convinced of the correctness of Wanner's judgment, and believe that the complicated tectonic conditions must be ascribed to reasons other than overthrust.

There are, perhaps, areas in North Borneo of local upthrust and overthrust; for example, in the river basin of the Sarudong-Kalabakang (Reinhard, 1924), though in this case not in the Danau Formation but in complexes of Tertiary strata. It also seems that the pyramidal peak in the upper Blantian Valley, the conspicuous Tambuku (cf. Fig. 29), composed of steeply dipping amphibolite, rests unconformably on a broad shoulder formed of radiolarian cherts and serpentines. This, at any rate, was the impression given by a brief ascent of Tambuku undertaken chiefly for surveying purposes. The area needs to be exhaustively examined, however, before far-reaching conclusions are drawn. But even now it may be very definitely assumed that overthrusts occur nowhere in North Borneo on anything like the scale of alpine nappes. The fact that the ophiolites, so extremely sensitive to shearing stress, show no recognizable traces of dynamothermal metamorphism, likewise testifies against nappe structure in the Danau Formation. Despite strong imbrication, brecciation and slickensiding, the ophiolites are not foliated, and such fine textures as, for example, those of the spilites, are not obliterated. Moreover, we have not succeeded in demonstrating the presence of any regular tectonic pattern. The impression gained is that all the rocks concerned, ophiolites as well as sediments, were chaotically pressed together and kneaded into one another. However, in spite of the unquestionably strong diastrophism to which these rocks have been subjected, it seems most unlikely that folding alone could produce such a chaotic assemblage, and it appears far more likely that these manifestations are connected with the intrusion of the ophiolites. The still partly unconsolidated sediments were subjected to subaquatic penetration, from below and probably also laterally, by basic magmas, which crumpled and intermingled with them, especially where, in consequence of the high vapour pressure of the magma, saturated in carbonic acid and water, ophiolitic breccias and tuffs were formed and pressed in or through the sediments. Moreover, subaquatic landslides (slumping) might have occurred. It is quite possible that the intimate mixing of basic magma with sedimentary material, impregnated with seawater, led to the forming of complex emulsions, which brought about reactions between the heterogeneous components—magma, sedimentary material and seawater—in which the spilite reaction, assumed and verified experimentally by Eskola (1935), may have played a part. The high carbonic acid, water and soda content of the ophiolitic-spilitic magmas is, therefore, perhaps not wholly juvenile-magmatic in origin.

Solutions rich in silica and carbonate, locally saturated with iron and manganese salts, may have been added later to the sea-water. They will have brought about metasomatic re-mineralization in the course of their migration through the ophiolites and the sediments bordering them, and caused colloidal deposits of silica and carbonate ooze, with sporadic accumulations of iron and manganese. The solutions, rich either in silica or in lime, which were added to the sea-water, gave rise to conditions very favourable to the development

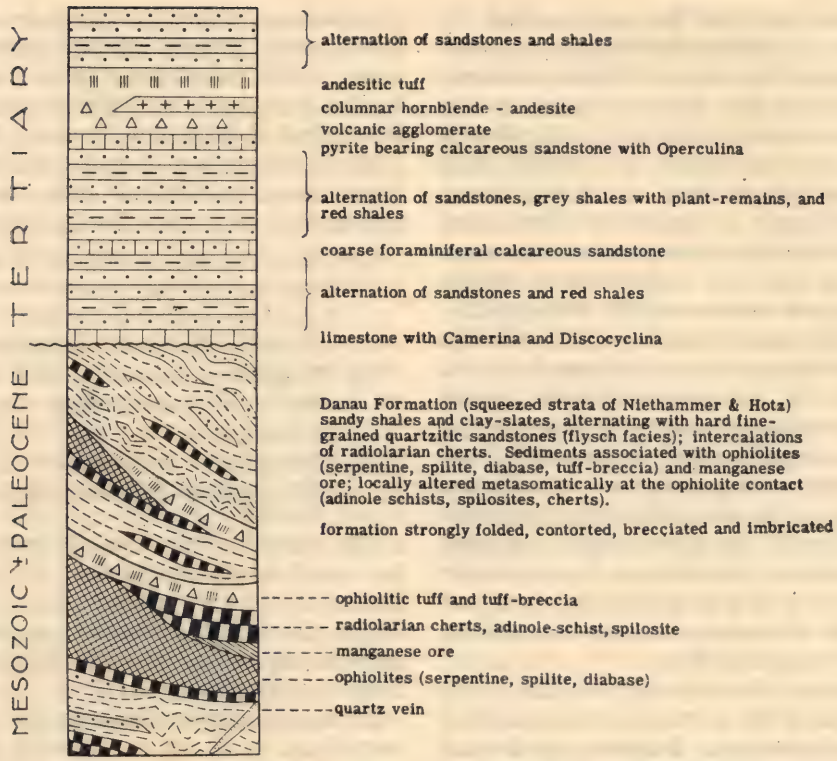

MESOZOIC ? PALEOCENE
TERTIARY
alternation of sandstones and shales
andesitic tuff
columnar hornblende - andesite
volcanic agglomerate
pyrite bearing calcareous sandstone with Operculina
alternation of sandstones, grey shales with plant-remains, and red shales
coarse foraminiferal calcareous sandstone
alternation of sandstones and red shales
limestone with Camerina and Discocyclina
Danau Formation (squeezed strata of Niethammer & Hotz) sandy shales and clay-slates, alternating with hard fine-grained quartzitic sandstones (flysch facies); intercalations of radiolarian cherts. Sediments associated with ophiolites (serpentine, spilite, diabase, tuff-breccia) and manganese ore; locally altered metasomatically at the ophiolite contact (adinole schists, spilosites, cherts).
formation strongly folded, contorted, brecciated and imbricated
ophiolitic tuff and tuff-breccia
radiolarian cherts, adinole-schist, spilosite
manganese ore
ophiolites (serpentine, spilite, diabase)
quartz vein

Fig. 28. Schematic stratigraphical column, southern part of Kudat Peninsula
(*After G. Niethammer* 1914)

of radiolaria and globigerina. The fragile shells settled together with the colloidally deposited silica-gel and carbonate ooze, and muds formed, rich in radiolaria and globigerina which are now to be found associated with the ophiolites as radiolarian cherts and globigerina marls. Thus we reach conceptions similar to those expressed by Lotti as long ago as 1886 (p. 128), later by Dewey and Flett (1911) and after them, in particular, by Davis (1918), Beskow (1929), Gilluly (1935) and others. In contradiction to Steinmann (1905) and Molengraaff (1909), we see no reason for regarding the radiolarian cherts as deep-sea sediments. The areas in which radiolarites occur in North Borneo are certainly very extensive, but the individual exposures are always of small dimensions and rarely suggest that they form part of a bigger occurrence. Nowhere is it possible to follow up beds of radiolarites for considerable distances. One cannot refrain from thinking that their genesis was due to locally favourable conditions. Their occurrence is bound up with that of the ophiolites, which are likewise widely distributed but small in individual outcrop.

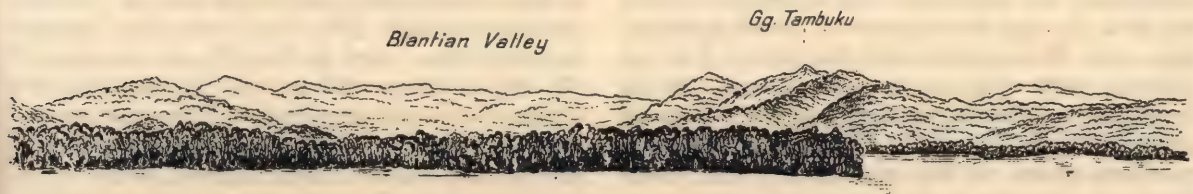


Fig. 29. Sketch of Gg. Tambuku, seen from P. Sebatik
After a sketch by M. Reinhard. The summit of Gg. Tambuku consists of amphibolite which rests unconformably, as an outlier, on radiolarian cherts and ophiolites of the Danau Formation forming the broad shoulder of the mountain.

From our description of the way in which the ophiolites occur, it follows that they partly penetrated or permeated the unconsolidated sediments beneath the water. But greater magma masses must also have remained embedded in the already consolidated older sediments, and would have crystallized more slowly under the thicker cover. There are accordingly, as has already been mentioned in describing the ophiolites, transition types present between extrusive and intrusive bodies, whose origin is due to one and the same process.

In mountain systems of Alpine type the ophiolites have penetrated the geosynclinal deposits at the commencement of magmatic-orogenic cycles. Neither the sediments accompanying the ophiolites nor the younger deposits are of any great thickness in North Borneo. No geosyncline was formed, and for this reason no nappe-forming orogenesis, nor any associated oro-metamorphic changes, appeared. The Malay Archipelago has repeatedly shown, in the course of geological time, a tendency to orogeny of an Alpine type, but the outcome has never been other than abortive.

No conclusive observations are available as to the time sequence of the intrusion and extrusion of the various ophiolite types. It appears, in the case of certain ophiolite occurrences, as if the gabbros were younger than the diabases and spilites. If, however, one pictures the history of the Danau Formation as already discussed, the conclusion will be reached that the various ophiolitic rock associations of North Borneo hardly permit a classification into an intrusion and differentiation system which is valid for all of them. This is, however, a problem to the solution of which geological exploration of the country has so far made no contribution.

In conclusion, the question of the *age of the Danau Formation* may again be raised. The most typical sediments of the Danau Formation, the radiolarian cherts, which were almost certainly deposited during the formation of the ophiolites and are therefore of the same age, contain no fossils apart from the radiolaria, and consequently yield no data for age determination. Reddish-brown, grey and whitish-red-flamed limestones and calcareous marls occur in close connection with the radiolarites, either in the beds overlying them, or replacing them laterally, as in the islands off the northern point of the country, on the Kudat Peninsula and also in Burong Island north-east of the Klias Peninsula (cf. Fig. 20). Thirty samples were available, which have all been examined in thin section. About two-thirds proved to be non-fossiliferous. Eleven samples contained a microfauna, which have been subjected to examination by the micropalaeontologist of the University of Basel, Prof. Reichel (see Appendix III).

His investigations show that the limestones and marls may be divided into three categories, according to their microfossil content:

(1) Those containing remains of small foraminifera, besides the predominating radiolaria. Age: Cretaceous to Tertiary, or perhaps, and still more doubtfully, Mesozoic to Tertiary.
(2) Globigerina limestones with the remains of other small foraminifera. Age: Cretaceous to Tertiary.
(3) Globigerina limestones with *globorotalia*. Age: probably Paleocene to Lower Eocene.

The samples of the third category all come from the small island of Burong, N.E of the Klias Peninsula, on the west coast of North Borneo, where the marly limestones occur in the bed immediately and conformably overlying the radiolarites (cf. Fig. 20).

It may be concluded that on the evidence of the microfauna it is not yet possible to define with certainty the age of the limestones and marls accompanying the radiolarites. It can be said only of the limestones overlying the radiolarian cherts on Burong Island that they are, in all probability, Paleocene.

According to Hotz and Niethammer the radiolarites and ophiolites occur in a complex of sandstones and shales subjected to extremely strong tectonic forces, which, on account of the strong mechanical strains exhibited, they term " squeezed strata " and consider to be of the same age as the radiolarian cherts, allocating them accordingly to the sediments of the Danau Formation. They conjecture that this sandstone-clay-slate complex, which looks like flysch, is older than Tertiary, and are inclined to allocate it to the Cretaceous. Silicified remains of small foraminifera were proven, as has already been mentioned (see p. 65) in a sandstone sample (Nh. 193) from this complex (see also Figs. 3 and 4, Plate I). A specimen of silicified limestone with remains of small silicified foraminifera also comes from the " squeezed strata " (specimen Nh. 386 from the Kalibangan River, a head-stream of the River Labuk, some 4 km. up-stream from Tampias, interior of N. Borneo). According to verbal information kindly given by Prof. Reichel, the foraminifera in each sample are

lepidocyclina of the group *L. sumatrensis Brady var. minor*, which would indicate that the strata are of Upper Oligocene to Miocene age. This is not to say that the whole complex of " squeezed strata " is of Tertiary age. It is much more probable that Tertiary sandstones and clay-slates have been folded and imbricated with older, similar rocks belonging to the Danau Formation. Hotz and Niethammer mention several instances where imbrication seems to have occurred. A clear example may be seen in cross-section No. 2 of Fig. 3.

The belt of Danau Formation to the N. of Kudat Harbour is accompanied on its southern border by a bed of Miocene limestones, south of which the strata complex shows a markedly uniform dip, in general to the south. The further south one advances, therefore, the horizons to which the strata belong should be younger. Nevertheless a calcareous horizon occurs on the S. edge of the map which, instead of being of yet more recent age, is as old as, or even somewhat older than, the northern calcareous horizon. As the Tertiary is generally strongly folded, and as in addition signs of imbrication are to be found elsewhere, both of the above-mentioned anomalies might have resulted from imbrication.

Limestones and calcareous sandstones rich in foraminifera are common in the Tertiary areas of North Borneo. They are lithologically and faunistically totally different from the limestones and calcareous marls of the Danau Formation. These Tertiary limestones and calcareous sandstones very often appear in the immediate vicinity of the Danau Formation. Typical occurrences are known to exist on the Banggi-Balambangan group of islands, which lie off the north of the mainland (cf. Enclosure III). In the Kudat Peninsula such limestones, rich in foraminifera, often border the occurrences of the Danau Formation (see, for example, Enclosure V, Fig. 28, and cross-sections 3 and 4 of Fig. 3). The same is true, according to Hotz and Niethammer, in the area of the Danau Formation on the west coast, whereas in the southeasterly occurrence of the Danau Formation, similar limestones have so far been encountered only on the Batu Tapadong on the middle Segama (Enclosure VIII) and on Gg. Madai on the W. coast of Darvel Bay (Enclosure IX).

The age of these limestones, as determined from their abundant microfauna, could be reliably established as Eocene and Miocene. Judging from the appearance of the outcrop, these formations have been deposited transgressively on the Danau Formation. Rutten (1925b) has already established the fact that the limestones, often brecciated, contain rounded fragments of radiolarian cherts, and Schneeberger also confirms that the transgressive nature of these limestones is indubitable. So the Danau Formation must have been folded in pre-Eocene times and the Eocene to Miocene foraminiferous limestones have evidently been deposited on the highly irregular erosion surface of the Danau Formation.

The above considerations have established the upper age-limit of the Danau Formation of the west and north coasts as definitely pre-Eocene. Rutten (1925b) arrived at a like result from micropalaeontological investigations, since he writes (op. cit. p. 644): " I am inclined to think that the fact that the earliest known fossiliferous Tertiary sediments in Borneo invariably contain rounded radiolarite implies that the folding of radiolaria-bearing rocks must have taken place in the pre-Tertiary, and that it is not very likely that the radiolarites still developed in Borneo in the Tertiary ". It is true that the *globorotalia*-bearing limestones associated with radiolarites, which according to Reichel are of Paleocene to Lower Eocene age, were not yet known to Rutten. Had he known of them he would have written " pre-Eocene " for " pre-Tertiary ".

In spite of the transgressive character of the Eocene and Miocene limestones, no angular unconformity between them and the Danau Formation seems to be present. This is evidently to be ascribed to the circumstance that the Danau Formation and the Tertiary deposits were folded together very intensely.

The following observations seem to contradict the assumption of the pre-Eocene age of the Danau Formation: according to Hotz, sills or lava flows of basalt and dolerite of no great thickness (H. 113 and H. 114) occur conformably in relatively weakly folded Tertiary sandstones on the east coast of the Bengkoka Peninsula. The rocks do not differ from other basalts and dolerites, which belong indisputably to the Danau Formation. If the basalts and dolerites of the Bengkoka Peninsula belonged to the ophiolites, and the sediments in which they occur were actually of Tertiary age, probably Eocene or Miocene, the ophiolitic volcanism would extend even into the Tertiary period. This occurrence cannot be adduced for the determination of the age of the Danau Formation until the question as to whether or not the basalts belong to the ophiolites has been clarified (perhaps a more

recent independent volcanism is involved here) and until the age of the sediments enclosing them has been established. On the other hand, mention may be made of the important part it may ultimately play in establishing the upper age-limit of the ophiolites.

A similar case is offered by the basalt occurrences found by Roothaan and Wenk in the basin of the Milian (Kinabatangan) and Kuamut (cf. Enclosure VII). They appear as stocks in Oligo-Miocene sandstones and seem to be surrounded by quite a weak contact aureole. Unfortunately no samples of these occurrences are available, as all the material accumulated was lost in the confusion of war. According to the same authors, the gabbroid to peridotitic rocks in the Sinoa-Imbok area (southern tributaries of the Milian) and in the upper Karamuak have also intruded the Tertiary sandstones to form hornfels contacts and, near the copper mine on the Karang River in the upper Karamuak, even skarns. These discoveries would again indicate that ophiolite intrusions into the Oligo-Miocene sandstones have taken place in certain areas. But here, likewise, the questions remain open as to whether these intrusions still belong to the ophiolites, or whether we are dealing with Oligo-Miocene sediments which were altered at the contact to hornfelses and skarns.

Setting aside these cases which, although of importance in age determination, still remain doubtful, the age of the Danau Formation can thus be established in respect of the north-western part as pre-Eocene, probably Mesozoic to Paleocene.

The trips made over the SE. part of the Danau Formation have contributed less to settling the question of age, since fossiliferous sediments here seem to be less widely distributed. Reinhard found no calcareous sediments whatever in the Danau Formation of the Blantian river-basin. In the Segama and the rivers flowing into Darvel Bay, which lie either wholly or for long stretches in Danau Formation, fossiliferous sediments are known to occur at only two localities in connection with the Danau Formation. Stamm collected a sample of compact black limestone with greatly deteriorated remains of radiolaria, in the upper region of the middle course of the Segama (cf. Enclosure VIII and Appendix No. III). The limestone occurs in association with gabbro. No verdict can be given as to its age.

A cross-section examined by Stamm in the Tingkayu is much more revealing. Wanner (1921, op. cit. p. 171) has given a detailed description of it based on Stamm's notes and rock-samples. The section in question is shown in Enclosure IX. From this it may be seen that red and green globigerina marls with small nummulites occur in the immediate neighbourhood of ophiolites. No samples were available to us, but judging from Wanner's description, these marls and marly limestones correspond lithologically to the marls of the Danau Formation described above, though they appear to be stratigraphically more recent, probably Upper Eocene, according to Wanner.

Let us briefly summarize all that is known to date regarding the age of the Danau Formation in North Borneo. On the evidence of the microfauna, the marls accompanying the radiolarites can be classified as Mesozoic to Paleocene, and in one case, that of the globorotalian marl, in all probability, as Paleocene. In the north the Danau Formation is older than the Eocene nummulitic limestones which transgress over the ophiolites. In the south-east, however, the Danau Formation appears to extend into the Upper Eocene. Reference has been made to cases, not yet clarified, of ophiolites which may be still more recent.

Results achieved by Dutch geologists regarding the age of the Danau Formation in Dutch Borneo may be quoted for purposes of comparison.

Molengraaff (1902) says that Cenomanian sandstones and marls with *Orbitolina concava Lam.* transgress over the West Borneo Danau Formation. Molengraaff is inclined, together with Hinde, the investigator of the radiolarites, to attribute a Jurassic age to the Danau Formation.

According to Zeijlmans (1939) the Danau Formation in west and Central Borneo embraces both Permo-Carboniferous and Upper Triassic formations, which each contain diagnostic fossils (*Fusulinidae*, *Calamites*, *Pecopteris* and *Monotis*, *Halobia*).

As a result of an examination of the rock and fossil samples collected by Witkamp on the Central-East Borneo Expedition of 1925, M. G. Rutten (1947) classifies the Danau Formation into an older and a more recent division. In the older division typical Danau rock-associations contain intercalations of partly re-crystallized limestones with Devonian fossils (loc. cit. p. 1). But in describing the Devonian fossils (loc. sit. p. 11), it is stated that the Devonian limestones occur on the edge of the Danau Formation, and it is therefore not wholly certain that they belong to it. The younger Danau Formation, says Rutten, consists of graywackes and conglomerates, with rock

components from the older Danau Formation. To classify these graywackes as Danau Formation because they consist of reworked rock material of the older Danau Formation, seems to us incorrect.

The characteristic rock associations of ophiolites with radiolarites, subordinate limestones and flysch-like sandstones and clay-slates, assigned by Molengraaff to the Danau Formation, seem, therefore, to have originated in Borneo at different times. The conditions necessary to produce such a rock-association have evidently been repeatedly fulfilled.

B. SLATE FORMATION

Both Hotz and Niethammer distinguished a " slate formation " when mapping the region of Mt. Kinabalu and the area to the south of it. They describe it as being invariably a strongly-folded complex of clay-slates, mostly indurated, more rarely soft, and sometimes in the form of roofing slates. Beds of graywackes and quartzites of varying thickness occur very frequently. The dark clay-slates are almost invariably intersected by a network of white quartz veins.

Ophiolites seem to occur very rarely in the Slate Formation, and then only to a very limited extent.

The main area occupied by them is situated—according to Niethammer's survey—in the Trusmadi mountains, south of Mt. Kinabalu, in the neighbourhood of the west coast. The Slate Formation seems to occur here in a window in the Danau Formation, with which it is marginally folded. Where Tertiary sediments transgress over the Slate Formation, these two formations are imbricated and folded together. In the continuation to the south-west of the main area of distribution, a few miles north-west of Keningau and on the Padas River at Tenom, clay-slates which have been subjected to strong tectonic forces occur once again within the Tertiary Formation in two eroded anticlinal crests of no great extent. The Slate Formation extends northwards along the western slope of Mt. Kinabalu and for a short distance only beyond this massif. The presence of the Slate Formation has also been confirmed by Niethammer in the upper course of the Makadau, a head-stream of the Sugut.

To the Slate Formation also belong, in all probability, the black to dark-grey shales, generally indurated, splintery and hard, mostly argillaceous or siliceous, rarely slightly calcareous, with intercalations of grey quartzites, grits and conglomerates and thin coaly films, which Bächlin, Schneeberger and Wenk encountered in the head-water area of the Sembakong at Pensiangan and Sapulut, near the Dutch frontier. These are the northern-most offshoots of the slate-quartzite series described by Munniks de Jongh (1913) as the Sembakong Formation, which is more extensive in the Dutch territory to the immediate south. Munniks de Jongh, as well as Bächlin and Schneeberger, mentions deposits of cherts and radiolarites embedded in the upper part of the Sembakong Formation.

The delimitation between the Slate Formation, the sediments of the Danau Formation and the Tertiary shale-sandstone complex is very uncertain in imbricated regions, as very similar rocks occur in all three formations, and transitions from the one formation to the other generally follow gradually. Thus, for example, Wenk states: the Kalabakang Formation represented in the lower and middle course of the Kalabakang river system (SE. coast of North Borneo) by dark, concretionary, crumbling sandy shales, occasionally alternating with sandstone beds, is much disturbed along the upper Tiagu, a left tributary of the Kalabakang, and at first becomes phyllitic along fault and shear planes only. In the head-waters, however, dark-grey phyllites and clay-slates replace the shales, and the interbedded sandstones become quartzitic. Phyllites and quartzites are veined with quartz, more rarely with calcite. In the joint fissures, inch-long quartz crystals were found. Evidently these alterations are due to low-grade dynamic metamorphism.

The examination of the rock samples has fully confirmed the difficulty of separating the three formations—Tertiary sediments, sediments of the Danau Formation and Slate Formation. It has been established that the samples of clay-slates, shales, quartzitic sandstones and schistose graywackes, collected by Hotz, Niethammer and Wenk, are derived for the most part from areas mapped as belonging to the Slate Formation, but that identical samples are also derived from the sediments of the Danau Formation and the Tertiary.

The microscopic examination of the thin sections yielded on the whole a very monotonous picture. The slates consist of minute grains of quartz and

feldspar with a clayey, carbonaceous cement. Quartz, and more rarely calcite, also occur in pockets and veins. In one sample collected by Wenk (Wk. 2, Batu Punggul, upper Sapulut) the calcite veinlets have been partly replaced metasomatically by quartz. No other instances of re-crystallization nor of the formation of new minerals have been detected in these rocks. More intensely foliated samples of a phyllitic appearance bear sericite, chlorite and occasionally talc. One bluish-grey phyllite consists of an extremely fine nematoblastic tissue of chlorite, talc, crocidolite and ilmenite skeletons. In another dark-grey phyllite the formation of minute scales of biotite can be observed. In these rocks of phyllitic appearance the formation of new minerals has evidently taken place, a fact which we are inclined to ascribe to weak dynamic metamorphism. It should further be mentioned that the foliated arkoses and graywackes, in addition to muscovite, quartz and plagioclase, also bear chequered albite in fair abundance.

Isolated patches of similar phyllitic rocks occur in a few other localities besides those already mentioned. Thus, a reef to the west of P. Meriangin Besar, at the SW. tip of P. Banggi (H. 3, Enclosure III), consists of sericite-quartz-phyllite. Phyllites also occur, together with serpentine, in the western part of the southern coast of P. Sakar (J. 221, Enclosure VIII) and yet again in the upper course of the S.Diwata (W. coast of Darvel Bay).

The age of the slates remains extremely problematic. No traces of fossils have been found in them. According to Schneeberger and Bächlin, the slates on the S.Tulit (upper course of the Sembakong, near the Dutch frontier) are overlain unconformably by Eocene basal conglomerates. Hotz and Niethammer stress the fact that the Slate Formation is much more intensely folded and foliated than the Tertiary deposits, and they therefore conclude, in accordance with the findings of Schneeberger and Bächlin, that the Slate Formation is older than Tertiary. We may assume this to be highly probable. The relationship between the Slate Formation and the Danau Formation, however, has by no means been clarified. It is possible that they are of the same age and differ only in their facies. The fact that in the Slate Formation phyllitic rocks, i.e. sediments with a characteristic epi-oro-metamorphic mineral content, are rather widespread, while they appear to be absent from the Danau Formation, seems to suggest a greater age for the Slate Formation. In accordance with this assumption, the slates have been placed below the Danau Formation in the Legend of the geological map (Enclosure I). That further grounds are needed for this assumption is quite clear from the foregoing discussion.

Rocks similar to those characterizing the Slate Formation are also fairly widespread in Dutch Borneo. There, too, the question of the age of the rock complex known as "Oude Leiformatie" (Old Slate Formation) has not been finally solved and has given rise to controversy. Ter Bruggen (1935) and M. G. Rutten (1947), on the basis of Eocene limestones embedded in the phyllitic rocks, suggest a Tertiary age, whereas Zeijlmans and Ubachs (1936) regard the "Oude Leiformatie" with some reserve, as Cretaceous and Upper Triassic.

C. CRYSTALLINE SCHISTS AND ASSOCIATED INTRUSIVE ROCKS

Preliminary Remarks

Crystalline schists occupy only a limited area in North Borneo. Apart from quite sporadic occurrences in the islands off the N. coast and in the Kudat Peninsula, they appear to be confined to the SE. of the country. Admittedly, we are less well informed concerning their distribution than we are concerning that of the other formations. Our geological knowledge of the country is derived almost exclusively from the investigations of petroleum geologists, who were not interested in exploring areas presumably constituted by predominantly crystalline rocks. So it is not impossible that crystalline schists occur also in areas other than those described in this report, especially in the interior of North Borneo, which has not yet been explored.

Great difficulties and uncertainties were encountered in the attempt to distinguish between the occurrences of crystalline schists and those of the ophiolites of the Danau Formation. The two formations are not differentiated in the reports and geological maps of the petroleum geologists, but are often united with the Tertiary volcanic rocks to form an "igneous and metamorphic rocks" group. The separation of the crystalline schists from the ophiolites and the Tertiary intrusive and

extrusive rocks had therefore to be undertaken almost exclusively on the evidence of the rock samples examined. Because of this, doubtful points were occasionally encountered, for certain types of rocks are as likely to appear in the one as in the other category. This applies, *inter alia*, to chlorite-albite schists, zoisite-epidote-actinolite schists and dioritic rocks. A selection of rock samples from the same locality was usually available, and in doubtful cases a decision was made, based on the rock assemblage, as to the formation in which an occurrence should be classified.

Gabbro and serpentine are such typical rocks of the Danau ophiolite series that " Danau Formation " is marked at every point on the geological map at which they appear. This is perhaps too great a simplification, because the possibility is not excluded that such rocks occur within the crystalline schists, and so belong to the old basement rocks.

It follows from what has been said that our knowledge of the crystalline schists and their distribution is still highly incomplete and provisional.

Age of the Crystalline Schists and Associated Intrusives

We have no evidence as to the age of the crystalline schists of North Borneo and the intrusives appearing in them. They seem, judging by occurrences so far known, to appear always in association with the Danau Formation, and in particular with its ophiolites; so the question as to whether they may represent a metamorphic facies of the Danau Formation is not without foundation. From the petrographical standpoint such an interpretation would be readily acceptable. The crystalline schists comprise hardly any rocks which do not bear hornblende either exclusively or at any rate in abundance, and which might very well be metamorphic derivatives of diabases, spilites and their tuffs, or of marly rocks. However, as has already been mentioned in discussing the ophiolites, these show no signs of dynamo-thermal re-mineralization. It seems very improbable that part of the ophiolites should have undergone such intense re-crystallization, that all trace should have been lost of the original mineral content and of the extremely characteristic textures, while in the immediate neighbourhood ophiolites appear with primary mineral content wholly intact and with characteristic igneous textures. It appears far more likely that the crystalline schists stand in no genetic relationship to the ophiolites, and that they are older, and represent remains of an old basement whose age cannot be more precisely defined. It is worthy of note that micaceous rocks seem to occur only very rarely among them. The dioritic intrusives which occur in close association with the metamorphic schists, might be syngenetic with the crystalline schists.

Occurrences of Crystalline Schists

Island group in the N. of North Borneo (cf. Enclosure III)

P. Manawali

The island seems to be almost entirely built up of typical rocks of the Danau Formation, ophiolites and radiolarian cherts. On the east coast, however, appears a finely-banded epidote-hornblende schist. The chief constituent is a bluish-green hornblende; less epidote and about an equal amount of sericitized plagioclase are present. There is little quartz, but an abundance of ilmenite. The rock shows coarse nematoblastic texture. A greyish-green, splintery, chlorite-schist comes from the north coast. It consists of a fine nematoblastic fabric (grains diam. $\sim$ 0·02 mm.) of chlorite, quartz and leucoxene, with " splashes " of calcite and little veins of epidote. The rock is penetrated by numerous shearing planes. We are dealing here with a very weakly epi-metamorphic rock, and it is doubtful whether it belongs to the group of adinole schists, i.e. to the Danau Formation, or to the old crystalline schists, among which it has been figured on the sketch-map (Enclosure III).

P. Banggi

From this larger island, on which the rocks of the Danau Formation are also very common, come two amphibolite samples. In approximately the middle of the west coast, to the north of the bay into which the River Limbuak flows, occurs an almost massive, slightly schistose, finely microlitic amphibolite with a few hornblende xenoblasts up to 3 mm. in size. The nematoblastic felt consists mainly of small, bluish-green hornblende needles and of a little quartz, plagioclase and epidote. The hornblende xenoblasts are olive-green in colour with a bluish-green fringe.

From the north coast, immediately to the east of K. Sibumbung, comes a weakly schistose and splintery, almost aphanitic, amphibolite. The nemoblastic felt consists predominantly of small, bluish-green columnar crystals of hornblende, little plagioclase, quartz and epidote with distinct foliation caused by re-crystallization. It appears to be a purely local occurrence.

Kudat Peninsula (cf. Enlosure IV)

From the east coast of the Kudat Peninsula, 4 km. north of Kudat, come two samples of fine-grained amphibolites. One is a banded amphibolite. The blackish-green bands consist exclusively of bluish-green hornblende and thickly dusted plagioclase; the light greenish-grey bands are of predominantly acid, mainly untwinned fresh plagioclase, less diopside, and calcite. The other sample is a plagioclase amphibolite consisting

of approximately equal parts of bluish-green hornblende and thickly-dusted untwinned plagioclase. Abundant ilmenite and a little leucoxene are present. These amphibolites occur in association with ophiolites.

On the south coast of Kudat Bay, in close association with ophiolites and ophiolite-contact rocks, leuco-quartz-diorites occur whose geological position is still quite uncertain. They have been described under the ophiolites on the assumption that we might, in the case of these rocks, be dealing with the most acid members of the ophiolite series. But mention was also made of the occurrence in the Segama of quartz-diorites amidst typical crystalline schists. It is, therefore, quite possible that the quartz-diorites of Kudat Harbour also belong to the old crystalline basement. The data and rock material at our disposal were not sufficient to settle this question.

INTERIOR OF NORTH BORNEO

Tributaries of the Kinabatangan-Milian

Roothaan and Wenk write in their reports of the occurrence of gneisses and hornfels in the Karamuak River (left-bank tributary of the Milian-Kinabatangan) and in the River Malua, a right-bank tributary of the Kinabatangan. Injection-gneisses, according to them, also occur beside typical Danau ophiolites in the River Sangitan, a right-bank tributary of the Kuamut. As no rock samples of these occurrences are to hand, and as the two authors have not separated the crystalline schists from the Danau Formation on their maps, we know no details about their distribution.

SOUTH-EASTERN PART OF NORTH BORNEO

The crystalline schists attain their greatest extension in the area around Darvel Bay, where they are shown to exist in broad continuous stretches in the middle course of the Segama, in the Telewas and in the rivers flowing into Darvel Bay. But here likewise we have little information as to their real extent, since the area of the upper course of the Segama has not yet been visited by geologists.

Middle course of Segama and Telewas Rivers (cf. Enclosure VIII)

Massive quartz-diorites to diorites occur over large tracts in both river-basins. The rock samples from the Telewas originate only from loose blocks. They differ in appearance and mineral content from the quartz-diorites which occur with ophiolitic rocks on the south coast of Kudat Harbour. The quartz-diorites and diorites of the Segama—and probably those of the Telewas as well—are associated with metamorphic schists, and thus very likely belong here to the old basement.

Whereas in the quartz-diorites of Kudat Harbour mafic minerals are altogether lacking, or are represented by chlorite and epidote, the quartz-diorites and diorites of the Segama-Telewas always bear hornblende, and in addition occasionally chlorite, epidote and, in small quantity, a very strongly pleochroic biotite as well. The hornblende may greatly predominate, and melanocratic, quartz-free types occur besides mesocratic rocks. The optical properties of the hornblende vary between the following limits: $n_\gamma - n_\alpha = 0{\cdot}016 - 0{\cdot}020$, $n_\gamma \wedge c$ 15°–18°; — 2V 70°–80°; n_γ bluish-green, n_β olive green, n_α light yellow, twinning on 100 occurs frequently. While the plagioclase of the Kudat quartz-diorites is very acid (albite to oligoclase), never zoned and occasionally exhibits strong saussuritization, the anorthite content of the plagioclases of the Segama-Telewas rocks fluctuates between 20% and 50%. Zoned structure is very common, with differences in An content up to 30% between the invariably basic core and the more acid outer zones. Albite and pericline twinning are both frequently represented; complex twinning according to the albite-Ala law also appears relatively often. Saussuritization does not occur, but sericitization is occasionally met with, the small flakes of sericite always being zonally arranged. One rock contains a small quantity of orthoclase and some grains of myrmekite. Titanite and ilmenite are always present in small quantities and a grain of orthite occasionally occurs. The calcite proliferations characteristic of the Kudat quartz-diorites are completely absent here.

Everything goes to show that the rocks of both quartz-diorite occurrences of Kudat Harbour and the Segama-Telewas exhibit very characteristic differences. It was to be expected that these differences might appear less pronounced in the chemical composition. However, one of the Segama quartz-diorites was analysed and yielded the following values:

L. 103. *Quartz-hornblende-diorite*

SiO_2	66·03	Segama River, 3 km. W. of Kuala
TiO_2	0·53	Telewas. Medium-grained rock
Al_2O_3	16·63	(diam. 2–4 mm.), mesocratic, plagio-
Fe_2O_3	1·51	clase conspicuously zoned, 40%
FeO	1·77	(core) to 25% An (rim), with slight
MnO	0·10	patchy sericitization, blue-green
MgO	1·63	hornblende, green pennine, little
CaO	4·48	epidote and titanite, one grain of
Na_2O	4·40	brown orthite. Small inclusion of
K_2O	1·27	granulitic texture, composed of
H_2O+	1·07	plagioclase, hornblende and a very
H_2O-	0·16	strongly pleochroic biotite (n_γ black,
P_2O_5	0·19	n_α light yellow).
	——	*Mode:* Quartz 24%, plagioclase
Total	99·77	66%, mafic minerals 10%. The
Sp. gr.	2·67	granulitic inclusion makes up 7%; it consists of plagioclase 69%, mafic minerals 31%.

Analysts: W. Vögtli and J. von Steiger.

Thus the chemical composition is similar to that of the Kudat quartz-diorites. The Niggli-values of the Segama quartz-diorite lie between those of the two analysed Kudat rocks (Table IX), except for the c value, which is greater in the case of the Segama quartz-diorite. This is not surprising, in view of the more basic plagioclase and the hornblende content.

Besides the massive varieties, gneissose quartz-diorites and diorites also occur. Their mineral constitution is the same as that of the massive rocks and, like them, the diorite-gneisses are also mesocratic. They merge into rocks with typical metamorphic textures and corresponding mineral composition. In the case of the plagioclase-epidote-hornblende-gneisses the plagioclase content (oligoclase) amounts to 50% to

60%, the balance being divided between epidote and hornblende ($n_\gamma \wedge c = 12°–16°$, $n_\gamma - n_\alpha = 0{\cdot}018$ — $0{\cdot}020$, n_γ bluish-green, n_β olive-green, n_α light yellow). Some pennine is constantly present, often showing parallel growth with the hornblende, ilmenite with a leucoxene rim, apatite, and occasionally a little pyrite and quartz. The texture is granoblastic to lepidoblastic. The plagioclase-hornblende-hornfels-gneisses differ from the rocks just mentioned by their pronounced granoblastic texture (identical with Fig. 3, Plate XIV), somewhat more basic plagioclase (30%–40% An), and by the sporadic occurrence of strongly pleochroic biotite. A flaser clinozoisite-amphibolite exhibits in thin section a streaky-flaser structure. The clinozoisite streaks are impregnated with limpid albite, which is only rarely twinned. The dark flasers consist of a proliferation of bluish-green, somewhat spotted hornblende and epidote, abundant rutile, little ilmenite, pyrites with haematite border and pennine.

The epidote-chlorite-schists, which are partly albite-bearing, exhibit a decided "epi"-character. Besides ilmenite and titanite, strongly pleochroic biotite and calcite may also occur as accessory constituents.

It is uncertain whether the actinolite-fels (L. 95) and the actinolite-talc-chlorite-fels (L. 97), both of which come from that section of the Telewas where the river bends from a N.–S. into an E.–W. direction, belong to the Old Crystalline or the Danau peridotites. As they occur together with dioritic gneisses, they have been classified as Old Crystalline.

The actinolite rock consists exclusively of megascopically dark-green actinolite, in thin section weakly coloured and faintly pleochroic. About 15% of the actinolite-talc-chlorite-fels illustrated in Fig. 1, Plate XIV, consists of almost colourless long prisms of actinolite up to about 2 mm. in size, which are embedded in a nematoblastic felt composed of equal parts of talc and chlorite with a little magnetite.

Lower course of the Segama

The course of the Segama River, which flows roughly W.–E. for a considerable stretch, bends in a NE. direction NNE. of Lahad Datu. The crystalline schists emerge once again for a short distance at about the middle of this north-easterly reach. Jezler (J. 148) and Leicester (L. 135) collected samples of actinolite-muscovite-schist from approximately the same locality. Some brownish-red garnet grains as big as peas are embedded in the well-foliated rocks. The predominating actinolite (50%–65% by volume) is moderately pleochroic with n_γ greyish blue, n_β greenish blue and n_α light yellow, $n_\gamma \wedge c = 12°–16°$; $n_\gamma - n_\alpha = 0{\cdot}022–0{\cdot}025$; $-2V \sim 80°$. Muscovite, clinozoisite and quartz are about equally represented. Clinochlore, rutile and limpid, untwinned albite, occur as accessories. Garnet is not present in the thin sections.

Darvel Bay region

Outcrops of crystalline schists occur at different places around Darvel Bay. For example, according to the observations of Stamm and Leicester, this is the case in the immediate neighbourhood of Lahad Datu, but no rock samples are available from this locality.

A small to medium-grained saussurite-amphibolite comes from the north coast of P. Sakar (cf. Enclosure VIII). The actinolitic hornblende, which amounts to approximately 80% by volume, exhibits a moderate pleochroism, n_γ light grey bluish green, n_β light olive green, n_α light yellow, $n_\gamma \wedge c = 20°–22°$, $n_\gamma - n_\alpha = 0{\cdot}020–0{\cdot}022$, $-2V = 85°–90°$. It is very often twinned on 100. The remaining saussurite occurs in intergranular interstices. Without the condenser, it has an almost opaque greyish-black appearance. On applying the condenser, a few small grains of clinozoisite may be seen in a base showing fine aggregate polarization.

A fine-grained hornblende-plagioclase-schist, weakly brecciated, consists of approximately equal parts of thickly-dusted plagioclase, with minute clinozoisite granules and a strongly pleochroic hornblende, n_γ bluish-green, n_β olive green, n_α light greenish-yellow; $n_\gamma \wedge c = 16°$, $n_\gamma - n_\alpha = 0{\cdot}018$, $-2V = 75°–80°$. Clinozoisite-epidote and leucoxene are the only accessories.

A fine-flaked, greyish-green chlorite-fels with magnetite xenoblasts up to 6 mm. in size comes likewise from the north coast of P. Sakar. The clinochlore scales are often almost snapped through and are very pale greenish-light yellow pleochroic. $+2V = 0°–20°$, negative elongation, $n_\gamma - n_\alpha \sim 0{\cdot}009$.

A small island in Darvel Bay, *P. Tanna*, is built of fine-grained plagioclase-hornblende-hornfels. The mineral content consists of approximately equal parts of the two major constituents; the only accessory constituent is ilmenite. The plagioclase grains are limpid, faintly zoned, frequently untwinned or with albite and pericline lamellae, 30% to 40% An content. The olive-green hornblende exhibits strong pleochroism. Whether Danau Formation really occurs in the neighbouring islands, as shown on the geological map (Enclosure I), could not be verified, as no rock samples are available.

Stamm (Wanner, 1921, p. 168) speaks of the occurrence of hornblende-gneisses in the middle and upper course of the Sapagaya (cf. Enclosure VIII), where they occur together with dioritic and gabbro-like rocks and serpentines. As no samples of these gneisses are available, they were not shown separately on the map. From Stamm's observations, however, it appears questionable whether only Danau Formation occurs in the Sapagaya, as the map indicates.

Stamm (Wanner, 1921, p. 156) found in the upper course of the Silibukan (E. of Lahad Datu) pebbles originating from Tertiary conglomerates, which formed a complete catalogue of typical crystalline schists. Stamm mentions sheared gabbro, amphibolites, gneiss-like rocks and a piece of a mica schist. It is not known if or where these rocks occur as bed-rock.

Stamm also reports occurrences of crystalline schists on the rivers Madai, Dadong Besar and Subahan (Enclosure IX), but no samples from these localities are to be found among the rocks examined.

Delimitation of the crystalline schists from the Danau Formation is also particularly uncertain in the *Tingkayu river basin* (rivers Tingkayu, Subahan, Dadong Besar and Dadong Kechil, Madai) (cf. Enclosure IX). Accordingly, no attempt was made to separate the two on the detailed map by the use of different symbols. Whereas most of the rock samples from these river basins probably represent typical Danau ophiolites and sediments, such is not the case with two samples

from the Dadong Kechil. One (J. 215) is a very finely-laminated, dirty-green, nephritic actinolite-clinozoisite-schist. The rock consists principally of a finely nematoblastic felt of colourless to weakly greenish actinolite ($n_\gamma \wedge c = 17°$, $n_\gamma - n_\alpha = 0{\cdot}024$, 2V variable about n_γ (65°–100°). The clinozoisite occurs in small flasers and strings; minute leucoxene grains in clouds and clusters. The schistose plagioclase-hornblende-clinozoisite-gneiss (J. 216) exhibits a porphyroclastic texture. Porphyroclasts, up to 0·2 mm. in size, often with undulatory extinction or broken, of colourless to weakly greenish actinolite or, less often, of strongly brown-dusted plagioclase, lie in a fine mixture of small hornblende fibres, clinochlore and clinozoisite-epidote. Strands of powdery leucoxene often flow round the porphyroclasts. The fine-grained plexus is impregnated here and there by limpid untwinned albite.

River basin of the Tungku, S. coast of the Dent Peninsula

The most interesting types of metamorphic rocks were collected by Wenk in the rivers Tungku and Pungulupi, a tributary of the Tungku, and in the Mungkuou, a small river that flows into the sea west of the Tungku. Wenk has written the following comments on the occurrence:

" The samples of crystalline schists collected in the above-mentioned river basins come from the coarse pyroclastic rocks belonging to the upper part of Tertiary e. These volcanic-sedimentary formations consist, in the Tungku area, of volcanic (andesitic) breccias, agglomerates and conglomerates, which merge laterally into tuffites, and are also interbedded with tuffites and lava streams. The collected crystalline samples have been largely taken from the coarse agglomerates and conglomerates. These consist of blocks (diam. 10–100 cm.) in which andesitic material greatly predominates over sediments (sandstone, chert), ophiolites and metamorphic rocks—among which eclogites and amphibolites are particularly conspicuous —all of which lie embedded in a tuffitic cement rich in lapilli and occasionally foraminiferal. The formation in question is the result of highly explosive Miocene volcanism, which produced not only magmatic material, but also threw out blocks of the Tertiary and pre-Tertiary underlying rock, which were deposited in the sea, where they were reworked and later formed part of a more recent sedimentary formation.

In the Tungku area, especially in the River Pungulupi, the Danau Formation, consisting of radiolarian cherts and ophiolites, was found *in situ*. In addition, outcrops of garnet-gneisses are also present. The samples collected from these bed-rocks have unfortunately been lost ".

The rocks most typical of this area are the carinthine-eclogites, of which five different samples are available. We are dealing here with massive, small- to medium-grained, dark-green rocks with garnet xenoblasts, dark brownish-red in colour, as big as peas and in one case as big as a hazelnut. The figures on Plate XV show thin sections of these eclogites, whose microscopic physiography is as follows:

The three major constituents, garnet, omphacite and carinthine hornblende, are present in approximately equal amounts, a proportion not subject to any considerable variation. The fabric, however, differs in all the samples examined. The faintly pale-red, rounded or scalloped garnet xenoblasts, which look as if they had melted at the edges, contain chiefly inclusions of ilmenite, titanite, rutile, carinthine, brown hornblende, omphacite, apatite and zoisite. They are always coated with a narrow micro- to crypto-crystalline kelyphite rim which penetrates also along fissures. The kelyphite consists of small, worm-like crystals of pale bluish-green hornblende, ore and plagioclase. A narrow corona of bluish-green hornblende grains may occasionally be observed round the kelyphite rim.

The light greyish-bluish to greenish-yellowish, hardly perceptibly pleochroic omphacite, is mainly equigranular. The polygonal grains (diam. ~ 0·2–0·4 mm.) are often surrounded by a narrow rim of carinthine or by a bluish-green hornblende. The powerfully pleochroic carinthine is heteroblastic, the size of grain varying between 0·1 mm. and 5 mm. Where grains of carinthine adjoin the kelyphite rims, they change at the edges into greenish-blue hornblende. The two constituents, omphacite and carinthine, are never evenly distributed in the rock, but are always found in clusters and occasionally in lines. The following optical properties were determined:

Omphacite $\wedge$ n_γ : $c = 41°–49°$; $n_\gamma - n_\alpha = 0{\cdot}018–0{\cdot}022$; $+2V = 60°–65°$; dispersion $\rho > v$ distinct around one axis, none observable around the other.

Carinthine: n_γ dark green olive, n_β dark brown olive, n_α light yellow; $n_\gamma \wedge c = 13°–17°$; $n_\gamma - n_\alpha = 0{\cdot}017–0{\cdot}021$; $-2V \sim 80°–85°$.

The component next in importance is plagioclase, which is never entirely absent and can at times amount to 15% by volume. The limpid grains are always strongly spotted, often reversely zoned. The An content varies between 55% and 80%. Ilmenite is often abundantly present; epidote, zoisite, apatite, rutile and titanite occur as accessories.

Some of the samples plainly exhibit deformation after crystallization. The kelyphite rim may be stripped off in the form of tails and concentrated in the strain shadow. The hornblende and pyroxene grains exhibit strong undulatory extinction or have decomposed into a fine-grained plexus. Cataclastic structure is very noticeable in a feldspathized carinthine-eclogite (Figs. 2 and 3, Plate XV). The limpid, rarely twinned plagioplagioclase (5% to 20% An, 35% by volume; the portion represented in the illustration is poor in plagioclase) occurs in finely granulated pockets and flasers. Both sample and thin section give the impression that feldspar has been introduced. The garnet and omphacite exhibit the same properties as they do in the carinthine-eclogites. Both are generally surrounded by a narrow rim formed of grains of bluish-green hornblende, which also infiltrates into the cracks. In the strain shadow of the omphacite grains, a brush-like tail of finely granulated, bluish-green hornblende is frequently to be seen. The optical properties of the carinthine lie within the limits given for the other eclogites, only the pleochroism seems less strong and the grains are powdered with ilmenite dust distributed in clouds. Exsolution, that is to say, separation from solid solution, might have been active here, conditioning the less marked pleochroism. The carinthine plates are frequently warped and drawn out marginally in course of foliation into a brush-like tail of grains which

merges into the plagioclase mosaic and passes over into bluish-green hornblende.

Two samples of medium-grained, massive *meladiorite* are almost identical both megascopically and in thin section. They consist of some 60% of hornblende, $n_\gamma : c = 14°–15°$; $n_\gamma - n_\alpha = 0{\cdot}021–0{\cdot}023$; n_γ dirty-green, n_β dirty olive green, n_α light-yellow; $-2V = 75°–80°$. The plagioclase, sprinkled with brown dust, which amounts to 40%, occurs in clusters of small serrated grains. It is frequently zonally spotted; the An content varies between 30% to 40%. Ilmenite, titanite, rutile and apatite are accessories. Zeolite and chequered albite occur along hair-like cracks and in pockets.

Two samples of plagioclase-hornblende-gneisses are markedly different in appearance. One has a pronouncedly heteroblastic structure, with hornblende xenoblasts up to 2 cm. in length. The rock consists of 35% plagioclase (4% to 10% An), in part cloudy, untwinned with muscovite microlites in small clusters, 30% quartz, 25% hornblende, $n_\gamma \wedge c = 10°–16°$; $n_\gamma - n_\alpha = 0{\cdot}019$; n_γ deep greyish-blue, n_β deep green, n_α light yellow, $-2V \sim 80°$, 10% clinozoisite epidote; as accessories, pennine, ilmenite, and one grain of garnet, partly altered into pennine.

The other sample is a banded garnet-bearing plagioclase-hornblende-gneiss of granoblastic texture. Streaks devoid of hornblende alternate with others bearing it. The plagioclase is fresh (14% to 23% An), permeated by globules of hornblende and quartz and occasionally clinozoisite, and indistinctly twinned. The light red garnet is likewise heavily speckled with quartz globules. The hornblende is strongly pleochroic, n_γ dark bluish-green, n_β dark-green, n_α light-yellow, $n_\gamma \wedge c = 16°–19°$; $n_\gamma - n_\alpha = 0{\cdot}018$. Rutile in moderate abundance occurs accessorily with ilmenite; apatite appears occasionally.

As the light constituents diminish, the rocks pass over into amphibolites, the four available samples of which were examined.

One coarse-grained amphibolite consists of some 80% of strongly heteroblastic hornblende (diam. 0·5–8 mm.), n_γ intense bluish-green, n_β olive green, n_α light yellow; $n_\gamma \wedge c = 16°–17°$; $n_\gamma n_\alpha = 0{\cdot}020–0{\cdot}025$, $-2V$ 80°–85°. The fresh plagioclase (67% to 90% An) participates to the extent of 10% by volume, as does also a pale greenish pyroxene. A few small grains of titanite occur as the only accessory.

A small-grained amphibolite, with weakly indicated foliation caused by re-crystallization, contains about 70% hornblende, n_γ dark-green, n_β yellowish-green, n_α light yellow; $n_\gamma \wedge c = 15°–18°$; $n_\gamma - n_\alpha = 0{\cdot}019–0{\cdot}021$; $-2V = 80°–90°$. The fresh plagioclase (25% by volume, 70% to 80% An) forms pockets and flasers with honeycomb texture. Titanite is present in abundance ($\sim$ 5%), whereas diopside occurs only in a few small grains (colourless, $n_\gamma : c = 42°$; $n_\gamma - n_\alpha = 0{\cdot}026$).

A fine-grained, massive amphibolite consists of 70% of hornblende, 20% plagioclase and 10% zoisite and clinozoisite. Titanite, and to a lesser extent rutile partly altered into ilmenite, occur accessorily. The texture is heteroblastic; rounded to oval grains of hornblende (diam. $\sim 0{\cdot}5$ mm., n_γ intense bluish-green, n_β green, n_α light yellow; $n_\gamma \wedge c = 14°–16°$, $n_\gamma - n_\alpha = 0{\cdot}020$) lie in a very fine-grained plexus of hornblende, zoisite and plagioclase. The plagioclase is limpid, strongly undulatory, often warped, generally untwinned and on that account very like quartz. The anorthite content varies between 65% to 75%.

One half of another sample of a massive amphibolite, which is likewise fine-grained, consists of granoblastic pockets of hornblende (diam. $\sim 0{\cdot}2$ mm., n_γ green, n_β yellowish green, n_α light yellow; $n_\gamma \wedge c = 14°–17°$; $n_\gamma - n_\alpha = 0{\cdot}020–0{\cdot}024$; $-2V \sim 80°–90°$); grains of ilmenite, often with a narrow border of titanite and isolated grains, or nests of grains, of fresh, frequently zoned plagioclase, with polysynthetic twinning lamellae (An content about 60%). Microdiablastic plates of bluish-green hornblende and plagioclase occupy the other half of the sample. A picture of a thin section of this amphibolite is given in Fig. 4, Plate XIV.

Two out of the three zoisite-amphibolites show porphyroclastic texture. In both cases green amphibole xenoclasts up to over 1 cm. in size lie in a fine-grained to almost compact matrix. The thin section shows that the often warped xenoclasts of actinolite of low iron content (pleochroism extremely weak, bluish-green/light yellow, $n_\gamma \wedge c = 16°–21°$; $n_\gamma - n_\alpha = 0{\cdot}020–0{\cdot}022$; $-2V = 80°–90°$) lie embedded in a matrix of finely pulverized actinolite, zoisite and basic plagioclase. Two different types of zoisite are present in one of the samples, one with small $+2V$, $\rho > v$, and straw-yellow interference-colour, the other with somewhat larger $+2V$, $\rho > v$ and indigo interference-colour.

The zoisite in the third sample exhibits, with $+2V = 15°–30°$, no axial dispersion, and normal interference-colours. A rim of myrmekite-like intergrowths of vermicular crystals of zoisite, with spinel, is occasionally to be found around the actinolite plates. Spinel is also abundantly present in the small-grained wavy matrix; garnet and clinochlore are locally distributed.

A single sample of a salite-edenite-hornfels, a megascopically compact, dark greyish-green rock, may be referred to here. It consists of approximately equal parts of a quite pale-greyish-green hornblende (edenite, $n_\gamma \wedge c = 17°–19°$; $n_\gamma - n_\alpha = 0{\cdot}019–0{\cdot}021$, $+2V = 80°–90°$); a pyroxene of almost the same colour (salite, $n_\gamma \wedge c = 40°$; $n_\gamma - n_\alpha = 0{\cdot}023–0{\cdot}026$, $+2V \sim 60°$) and fresh plagioclase (An content 60%–70%), together with some 10% spinel and a few small grains of ore. Micro- to cryptodiablastic pockets of hornblende and spinel or hornblende and labradorite are present in places.

It is evident from our description of the Tungku metamorphics that micaceous rocks are again completely absent. In the case of the Tungku rocks, conjectures as to the age of the eclogites and the other hornblende and pyroxene rocks are rendered all the more difficult by the fact that these rocks occur in a volcanic agglomerate. We might not exclude the possibility that the rocks described above represent contact-metamorphic derivatives of the ophiolites which have been subjected by the andesitic magma to complete re-mineralization at great depth and at corresponding pressure. In this case their origin and age would be different from that of the other crystalline schists.

Blantian River

The southernmost occurrence of crystalline schists on the east coast of the country was observed by Reinhard

in the upper Blantian Valley not far from the border of Dutch Borneo (cf. Enclosure X). It is a very limited occurrence of a saussurite-amphibolite showing linear foliation, the peculiar isolated position of which makes it especially interesting. The WNW. striking, steeply dipping amphibolite forms the pointed, pyramidal peak of G. Tambuku (cf. Fig. 29) in the upper Blantian Valley, rising from a broad, thickly-wooded shoulder, with poor outcrops of radiolarian cherts, sandstones and serpentine. The occurrence seems to be an outlier resting unconformably on Danau Formation. These observations are based on a very cursory survey, and consequently require verification. A more detailed exploration of the upper Blantian area might bring to light very important facts concerning the relationship between Danau Formation and the old crystalline basement.

The saussurite-amphibolite of Tambuku Peak consists of approximately 50% of an almost opaque saussurite. Twinning lamellae may still be seen by using the condenser. Inclusions of clinozoisite, prehnite and uralite needles are occasionally found to be in the saussurite. Chequered albite occurs in sporadic grains and limpid albite along fissures. The dirty, light bluish-green to colourless uralite exhibits hardly perceptible pleochroism; $n_\gamma \wedge c = 18°$, $n_\gamma - n_\alpha = 0{\cdot}024$, $-2V = 80°–90°$. It is to be found together with abundant clinozoisite and a little pennine and prehnite in pockets.

No crystalline schists were found as bed-rock along the reaches of the Blantian and Paninsau rivers so far explored. They were, however, encountered in the form of pebbles. A specimen of actionolite-fels of coarse prismatic habit, with actinolite crystals up to 2 cm. in length, and a pegmatite with weakly indicated graphic structure, derives from the Blantian. A pebble of a hornblende-chlorite-albite-gneiss comes from the Paninsau. The albite porphyroblasts (diam. 3 mm.) are limpid, seldom twinned, with minute inclusions of hornblende, less often of rutile, titanite and apatite. The grains are sometimes surrounded by a narrow border richer in An than the rest of the grain. The hornblende occurs in short prisms; n_γ light bluish-green, n_β light green, n_α light yellow, $n_\gamma \wedge c = 18°$, $n_\gamma - n_\alpha = 0{\cdot}024$, $-2V \sim 80°$. It is not homogeneous; specks which are a deeper blue in colour are less strongly birefringent. Clinochlore is present in about the same quantity as hornblende; the elongation is negative, n_α dirty, light bluish-green, n_γ colourless, $n_\gamma - n_\alpha = 0{\cdot}008$; $+2V$ very small. In addition to a little zoisite, grains of titanite and rutile are found in abundance. These pebbles suggest a wider distribution of crystalline rocks in the head-waters of the Blantian-Paninsau.

The presence of pebble terraces was observed by Reinhard in the head-waters of the Masmas, which flows into Cowie Harbour E. of the Blantian. These terraces bear, in addition to pebbles of radiolarian chert and serpentine, others of amphibolite and hornblende schist. This observation likewise suggests that crystalline schists may be widely distributed in the head-waters of the rivers Blantian-Masmas and Segama.

THE PLAGIOCLASE TWINS OF THE CRYSTALLINE SCHISTS

The relatively small number of plagioclase grains determined on the Fedoroff stage does not permit any conclusions to be drawn regarding the distribution of twinning laws in the types of crystalline schist described. Investigations were confined to an attempt to ascertain whether a difference in frequency existed between the twinning laws of sodic and calcic plagioclases. Such a difference does not appear to obtain. In both types, albite twins occur most frequently; then comes twinning according to the pericline and acline laws. Only one case of Carlsbad twinning was found, and none of Baveno or Ala twinning. The following table gives further information regarding the twinning laws determined and the frequency with which they appear.

TABLE X. FREQUENCY DISTRIBUTION OF THE PLAGIOCLASE TWINS IN THE CRYSTALLINE SCHISTS

Twin laws	Cryst. schists with sodic plagiocl.: An < 50%		Cryst. schists with calcic plagiocl.: An > 50%		All cryst. schists	
	Number of det. twins	%	Number of det. twins	%	Number of det. twins	%
Albite	41	53	8	38	49	50
Carlsbad	1	1	—	—	1	1
Complex Albite-Carlsbad	5	6	1	5	6	6
Pericline	11	14	7	33	18	18
Acline	17	22	1	5	18	18
Manebach	2	2	—	—	2	2
Complex Albite-Ala ..	—	—	4	20	4	4
Total of det. twins ..	77		21		98	

CHAPTER VIII

Final Remarks and Recommendations for Future Research

DURING the compilation of this volume many geological problems arose which are far from having been elucidated. Most of these problems were mentioned in the preceding chapters, and it is the special concern of the compilers of this volume to direct the attention of future explorers of North Borneo to some such fields of enquiry which deserve further treatment.

The areas covered by *pre-Tertiary formations* need thorough re-examination. Once a better knowledge is obtained, it has to be demonstrated whether the adopted threefold subdivision into crystalline schists and associated intrusives, Slate Formation and Danau Formation is to be maintained. The delimitation between these three formations is uncertain, and another subdivision would perhaps give more satisfactory results. Regions particularly suited to such investigations are: the south coast of Kudat Harbour (cf. Enclosure IV), where it should be determined whether the quartz-diorites belong to the Danau ophiolites or to the old crystalline basement; the Segama River and area west of Darvel Bay (cf. Enclosures VIII and IX) for the demarcation between Crystalline Schists, Danau Formation and Tertiary sediments; the Blantian valley (cf. Enclosure X) for the same purpose; also the Gg. Tambuku in the upper Blantian valley (cf. Enclosure X), a crucial point for establishing the structural relations between the old Crystalline Schists and the Danau Formation. The former seem to have been thrust so that they appear as an outlier on the latter.

Though the country has been repeatedly explored for mineral deposits, it is doubtful whether these surveys have been conducted systematically and scientifically. Most of the ore-deposits seem to be genetically related to the ophiolites of the Danau Formation. A careful investigation of the areas where these rocks occur might furnish some further indications.

The origin of the alluvial gold in the River Segama and in a few others that flow into Darvel Bay is as yet enigmatic. It would be of interest to know if placer gold is to be found in the older gravel terraces or even in coarsely clastic Tertiary sediments; for example, the pyroclastic layers of the Tabanak beds (cf. Enclosure VIII). In locating the occurrences of alluvial gold, it should be borne in mind that the courses of the rivers of this region have been subject to considerable changes from late Tertiary till quite recent times, as is convincingly illustrated by aerial photographs.

As the oil geologists exploring the country occupied themselves mainly with the Tertiary sediments, especially the Neogene series, these formations are comparatively well known. However, some points regarding the Tertiary sequence are not yet clear. Thus it will have been noted that the palaeontological support for the age of the Palaeogene series is poor. Beds of Tb age are proven. No beds exclusively of Ta age but only those of comprehensive Ta+b age have been confirmed; neither have strata of Tc and Td age been verified. Future research should determine whether these stages are really missing or only camouflaged by the barren arenaceous facies of a possibly comprehensive Palaeogene series. The highly interesting problem presented by the common occurrence of Tb and Te_{1-4} (or Te_5-f) guide foraminifera in the same rock samples has been discussed in Chapter V and Appendix II. Although in many instances one can offer the plausible explanation that the fossils of Tb age are reworked and, together with Eocene and pre-Tertiary rock fragments, were redeposited in beds of Te_{1-4} and Te_5-f age, this question, which is intimately connected with the apparent absence of Ta, Tc and Td beds, calls for further attention. In fact, a careful examination of the geological map of the Kudat Peninsula (Enclosure IV), shows that the age determined from the ranges of the larger foraminifera is hardly compatible with the results of field geology. This is particularly striking in the area occupied by the symmetrical anticline in the northernmost part of the peninsula, where the

stratigraphical succession worked out from palaeontological data is in contradiction to the sequence as supported by structural evidence.

To determine the exact age of the Kalabakang shales and fix the stratigraphical boundary between the pre-Tertiary ± Paleocene Danau Formation and the transgressive Eocene? (Tb), additional foraminiferal rocks must be collected and further palaeontological research carried out. Though many remote areas covered by Tertiary sediments have not been adequately explored, it is astonishing that the geology of the easily accessible Sandakan Peninsula is but little known. The excellent outcrops along the NW. shore of Sandakan harbour should particularly be examined in detail, both in view of the great thickness, an apparently complete sequence, and little disturbance of the Tertiary strata exposed there, and of the tuffitic intercalations reported from Berhala Island and from the immediate neighbourood of Sandakan town. The available aerial photographs would greatly facilitate this survey.

The *Tertiary igneous rocks* described in this paper derive from the intrusive body of Mt. Kinabalu in north-westerly North Borneo and from the volcanic areas in the south-east. Neither occurrence has been adequately explored and each deserves further examination. A survey of the intrusive body of Mt. Kinabalu, and particularly of its contact zones with the country rocks, is to be recommended. This work would be of great scientific, and possibly also of economic interest, since it would disclose whether any mineral deposits are connected with the Kinabalu intrusion. With this geological survey should be combined a study of the soils found in the foothills of the mountain. The quartz-monzonitic rocks of Kinabalu are rich in potash, and the average molecular ratio $\frac{K_2O}{K_2O+Na_2O}$ of some prominent rock types amounts to 0·5, which is the highest value ascertained in North Borneo rocks. As the igneous subsoil, the high daily precipitation and the altitude of the Kinabalu region offer conditions similar to those found in the Ceylon tea plantations, a study of the soils is to be recommended. Favourable terrains might be found to the SE. and E. of Mt. Kinabalu. A similar survey is advisable for the volcanic areas of the Simporna and Dent peninsulas. A map should be made of this area showing the fertile areas formed of fine-grained tuffs and tuffites, indicating their contact with the regions formed by coarse volcanic agglomerates, conglomerates and lava flows which originated from the same volcanic eruptions as the tuffs. These little-developed east coast districts offer much better soils than the predominantly sandy coastal plains in western North Borneo, which so far have served as the main agricultural land of the country. At the same time as the suggested survey of the soils and pyroclastic deposits of the Simporna and Dent peninsulas is carried out, additional samples of the foraminiferal tuffites and tuffite-breccias should be collected and palaeontologically examined so that the age of the volcanic activity may be more precisely established.

It is hardly necessary to draw the attention of coming explorers to the vast areas left blank on the geological map of North Borneo (Enclosure I). Such " terra incognita ", in both geological and topographical respects, is to be found mainly in the drainage areas of the three important rivers Padas, Labuk and Segama. These areas, in the oil companies' opinion, appeared to be of no interest; but, from the viewpoint of scientists and explorers for minerals, the Segama and Labuk regions, built, as it would seem, predominantly of igneous and metamorphic rocks, must certainly be a great attraction.

Plates

PLATE I

Tertiary fossiliferous sediments

1

H.2. Foraminiferal limestone, Tf (see Appendix II). Two sections of *Lepidocyclina* in the centre. South coast of P. Banggi, north of P. Pagasan (see Enclosure III). Without analyser (X 12).

2

H. 45. Foraminiferal limestone, Te_5-f_2 (see Appendix II). Various sections of *Lepidocyclina*; in the lower left-hand corner a specimen of *Lepidocyclina sumatrensis* (Brady). West coast of P. Banggi, south of Limbuak (see Enclosure III). Without analyser (X 12).

3

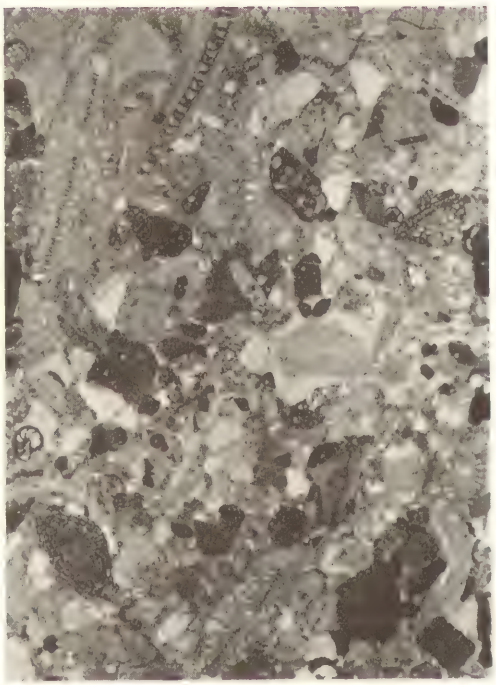
Nh. 193. Re-crystallised sandstone. Carbonate test of a *Lepidocyclina sumatrensis* (Brady) var. *minor* (L. Rutten) (det. M. Reichel) in part replaced by quartz. 6 km. ENE. from Kota Belud, NW. coast. Without analyser (X 16).

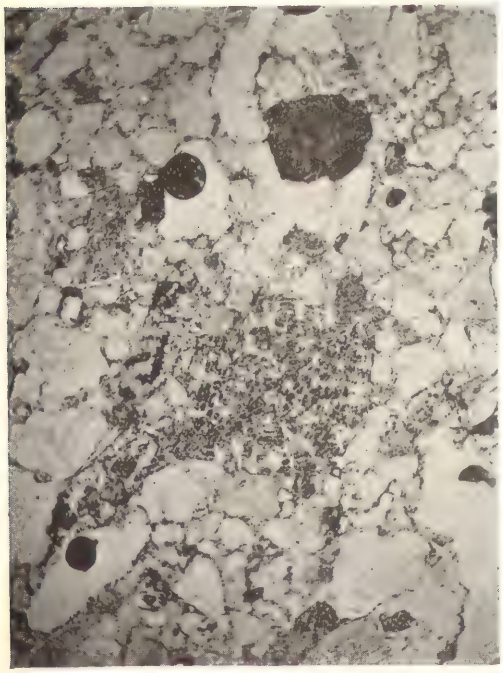
4

The same as Fig. 3, crossed nicols (X 16). The foraminiferal test is scarcely visible.

1

2





3

4

PLATE II

Tertiary fossiliferous andesitic tuffites (1 and 2)
Tertiary volcanic rocks (3 and 4)

1

Wk. 104. Foraminiferal slightly calcareous andesitic tuffite-breccia rich in vitric lapilli and with a few sub-angular fragments of plagioclase and pyroxene, 15% sedimentary material. *Miogypsinoïdes* cf. *ubaghsi* (Tan Sin Hok) in the centre of the figure. Middle course of S.Tungku, Dent Peninsula. Tertiary e. Without analyser (X 24).

2

L 124. Foraminiferal calcareous andesitic tuffite-breccia with vitrophyric lapilli and pyroxene crystals as main volcanic constituents, 50% sedimentary material. Specimens of *Spiroclypeus*, *Operculinella* and reworked *Discocyclinae*. Tertiary e_{2}-$_{3}$(+b) (see Appendix II). S.Segama below Batu Selawak. Without analyser (X 20).

3

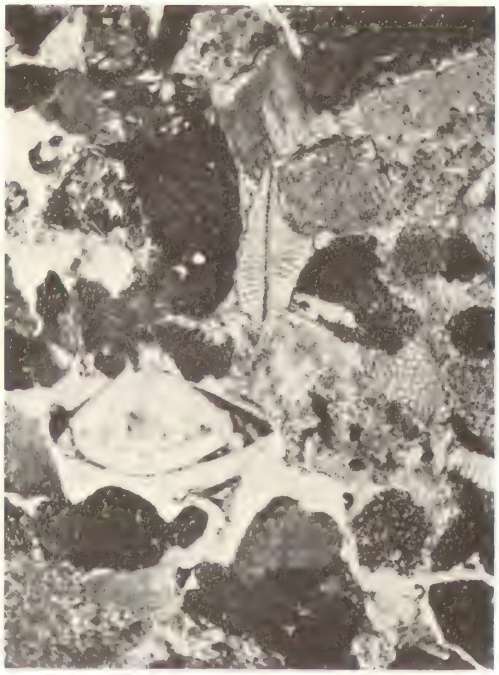
Sp. 124. Amygdaloidal, perlitic, hyalopilitic augite-bearing hypersthene-andesite, rich in glass. Bay SSW. Simporna, NE. Mt. Connor, Simporna Peninsula. Without analyser (X 12).

4

Wk. 33. Hyalopilitic hornblende - biotite - bytownite/labradorite - andesite, groundmass rich in tridymite. Block from volcanic agglomerate of S.Mung-kuou, Tungku area, Dent Peninsula. Without analyser (X 12).

1

2



3

4

PLATE III

Tertiary volcanic rocks

1

Sp. 110. Hyalopilitic biotite-hornblende-dacite. Strongly pleochroic phenocryst of biotite resorbed and surrounded by a corona of yellow-brown hornblende, plagioclase, ortho-pyroxene and iron ore. Western head-waters of S.Tawau, Simporna Peninsula. Without analyser (X 18).

2

Sp. 103. Fluidal hyalopilitic hypersthene-labradorite-dacite with relics of hornblende-phenocrysts. Batu Tinagat, 10 km. E. of Tawau, second rise from the coast, Simporna Peninsula. Without analyser (X 18).

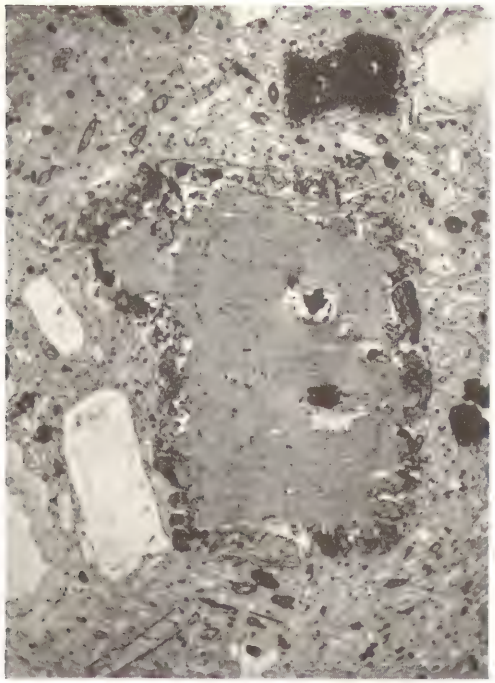
3

Sp. 115. Pilotaxitic augite-dacite with corroded phenocryst of augite, groundmass rich in pigeonite-augite. Western head-waters of S.Tawau, Simporna Peninsula. Crossed nicols (X 18).

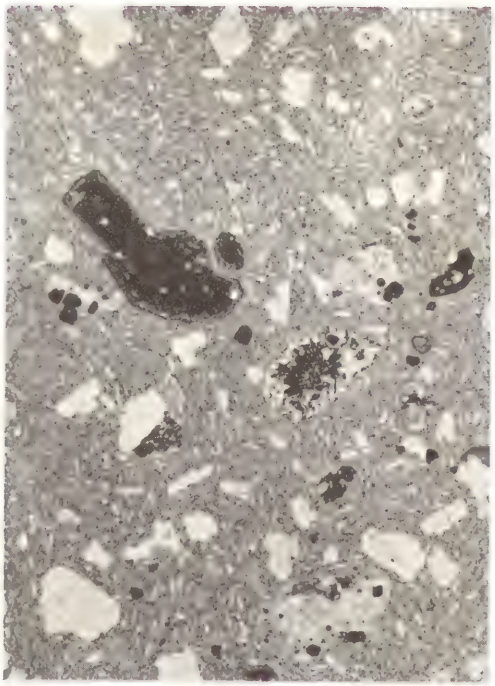
4

R. 81. Sub-doleritic hypersthene-basalt with groundmass rich in pigeonite-augite. Phenocryst of ortho-pyroxene corroded and surrounded by a corona of clino-pyroxene. S.Klumpang, 26 km. NNW. of P. Klumpang, Simporna Peninsula. Crossed nicols (X 24).

1



2



3

4

PLATE IV

Kinabalu intrusives

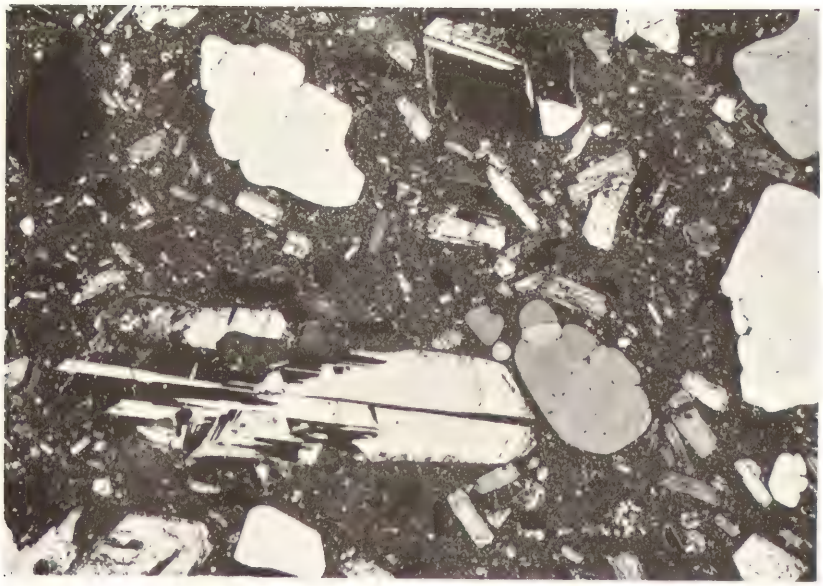
1

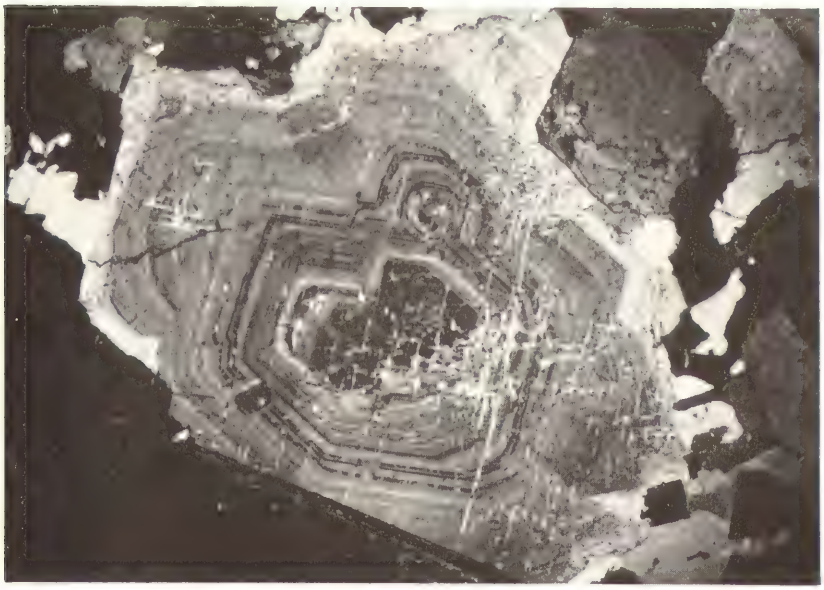
Nh. 423. Biotite-rhyodacite with phenocrysts of plagioclase and corroded quartz grains. Hill between S.Merali and S.Kenanapun, S. of Kg. Tadul, E. of Mt. Kinabalu. Crossed nicols (X 11).

2

Nh. 411. Plagioclase crystal showing oscillatory zoning, from coarse hornblende-quartz-monzonite of Mt. Kinabalu. Boulder found in S.Liwagu Kuananan, S. flank of Mt. Kinabalu. Crossed nicols (X 12).

1





2

PLATE V

Kinabalu intrusives
showing transitions into microgranitic border facies

1

Wk. 78. Coarse hornblende-biotite-quartz-monzonite. Boulder in S.Tampasuk near Kiau, SW. of Mt. Kinabalu. Crossed nicols (X 12).

2

Wk. 66. Medium-grained hornblende-biotite-granodiorite. Summit plateau of Mt. Kinabalu. Crossed nicols (X 12).

3

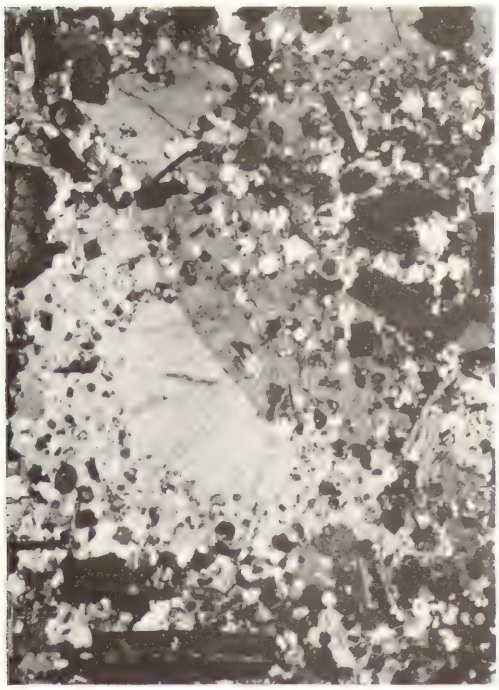
Wk. 68. Porphyritic hornblende-biotite-micro-quartz-monzonite. 250 m. below summit of Mt. Kinabalu, above Sayat-Sayat. Crossed nicols (X 12).

4

Wk. 64. Porphyritic hornblende-biotite-micro-quartz-monzonite. Summit of Low's Peak, Mt. Kinabalu. Crossed nicols (X 12).

1

2



3

4

PLATE VI

Danau Formation: sediments

1

Nh. 23. Radiolarian chert, crowded with radiolaria, with small veins of calcite. Tanjong Bangau, W. coast of Kudat Peninsula. Without analyser (X 12).

2

The same as 1, crossed nicols (X 12). The radiolaria are still clearly visible the filling with minute scales of chalcedony is conspicuous.

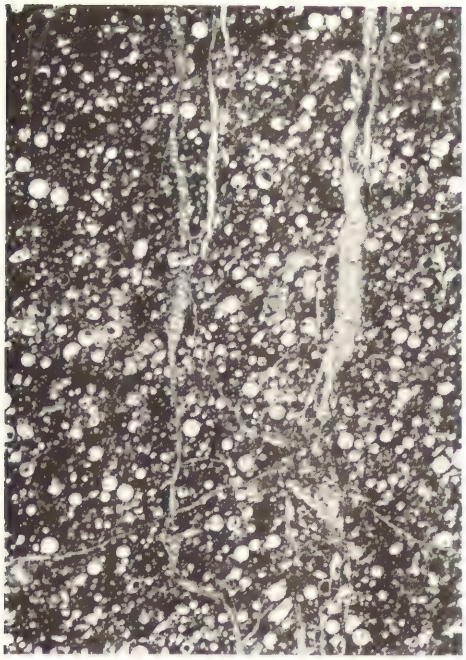
3

H. 31. Radiolarian chert, showing nebulous appearance of the radiolaria. SE. coast of Manawali Island, N. of Bengkoka Peninsula. Without analyser (X 12).

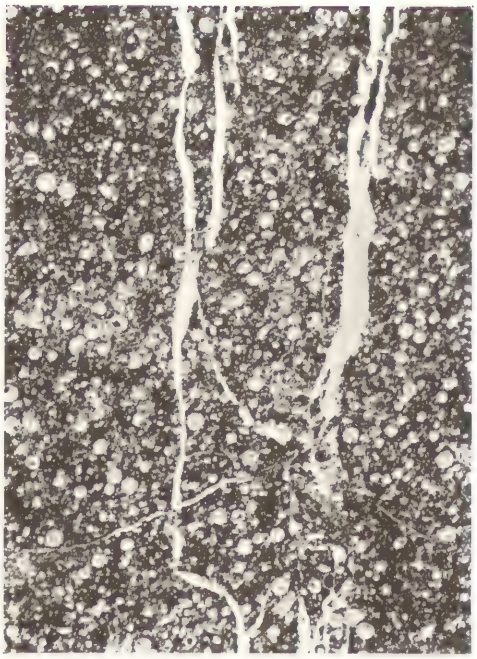
4

The same as 3, crossed nicols (X 12). The radiolaria are no longer visible on account of the complete re-crystallisation of the rock.

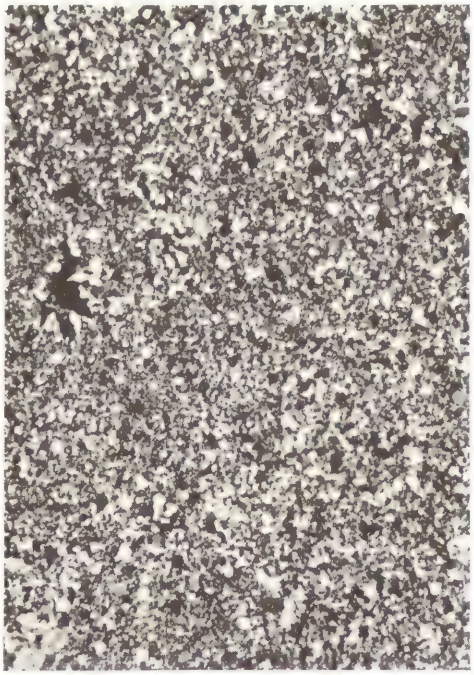
1



2



3



4

PLATE VII

Danau Formation: sediments and contact-metasomatic rocks

1

H. 142. Limestone with *globorotalia* and *globigerina* (determ. M. Reichel, cf. Appendix III). S. coast of Pulau Burong, N. of Klias Peninsula, W. coast of B.N.B. Without analyser (X 20).

2

Nh. 13. Vein of chalcedony in silicified serpentine. E. of Tanjong Bangau, W. coast of Kudat Peninsula. Crossed nicols (X 20).

3

Nh. 209. Spilosite. Microcrystalline aggregate of albite, quartz and sericite, maculose texture. Bukit Tampasuk, $2\frac{1}{2}$ km. E. of Kota Belud, W. coast of B.N.B. Without analyser (X 19).

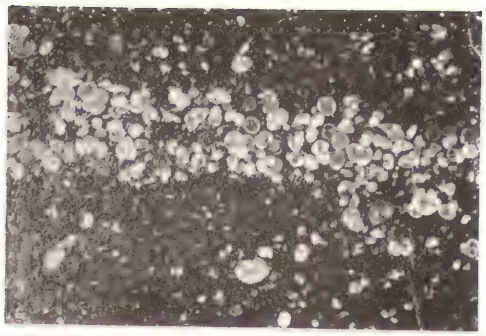
4

Nh. 100. Silicified and calcified dunite-serpentine. The typical texture of partly serpentinised olivine and of bastite is conspicuous. S. coast of Kudat Bay N. coast of B.N.B. Without analyser (X 19).

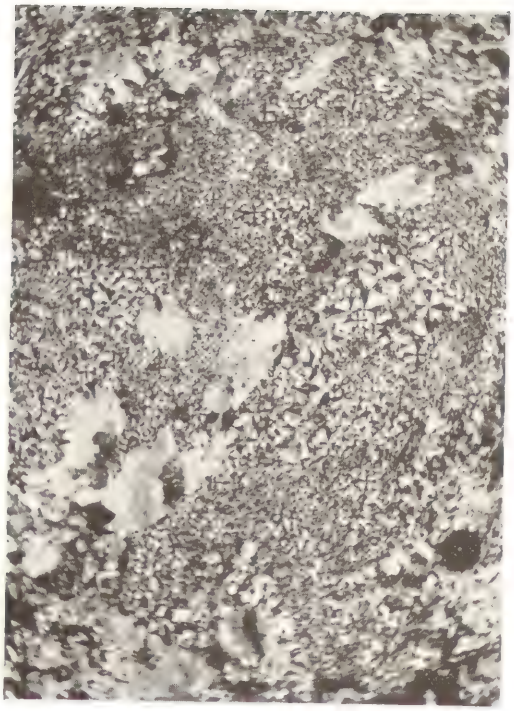
5

The same as Fig. 4, crossed nicols (X 19). On account of the complete metasomatic replacement of the olivine, serpentine and bastite by quartz and calcite, the typical texture of Fig. 4 appears obliterated.

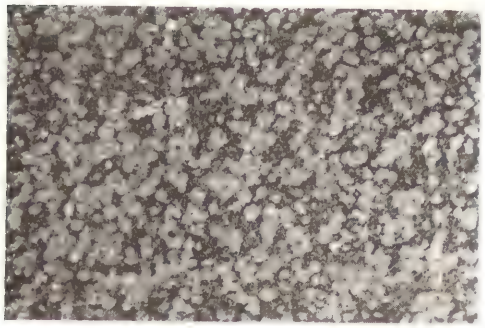
1

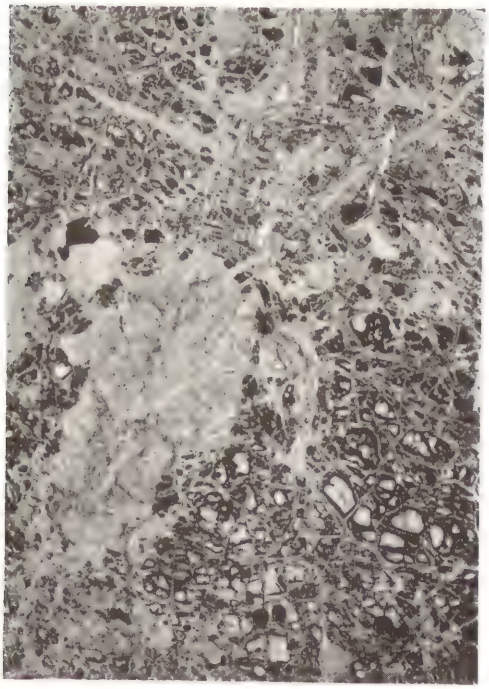


2

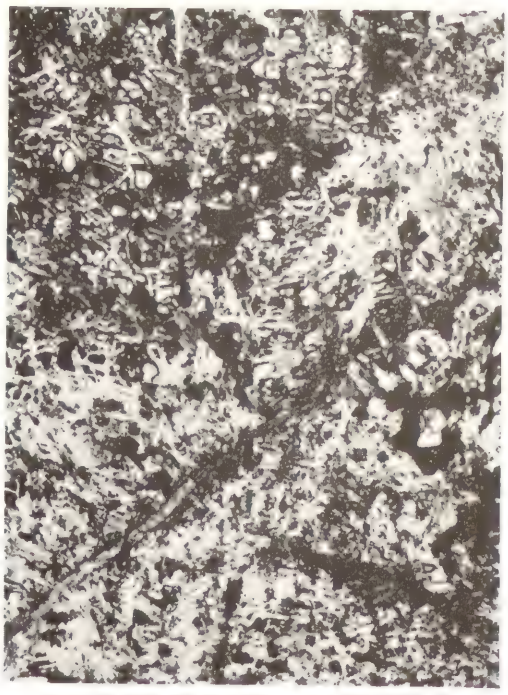


3





4



5

PLATE VIII

Danau Formation: intrusive ophiolites

1

R. 55. Gabbro with accessory olivine. Sub-ophitic texture. Blantian River, SE. coast of B.N.B. Without analyser (X 12).

2

The same as 1. Crossed nicols (X 12).

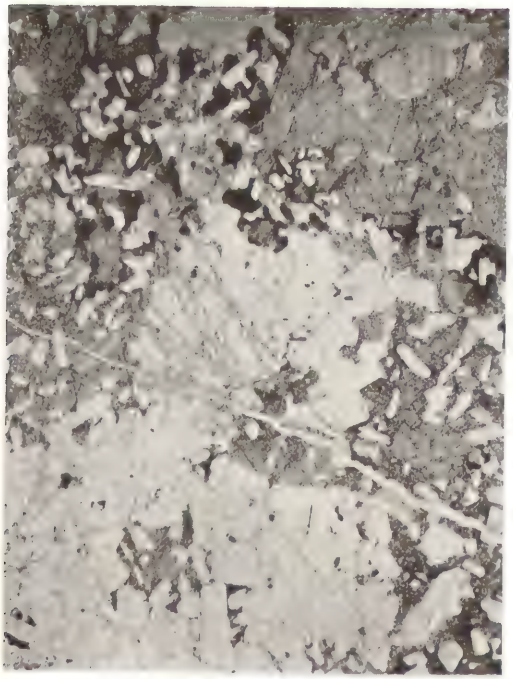
3

R. 43. Olivine-gabbro. Radiating cracks around more or less serpentinised olivine. Sub-ophitic texture. Blantian River, SE. coast of B.N.B. Without analyser (X 12).

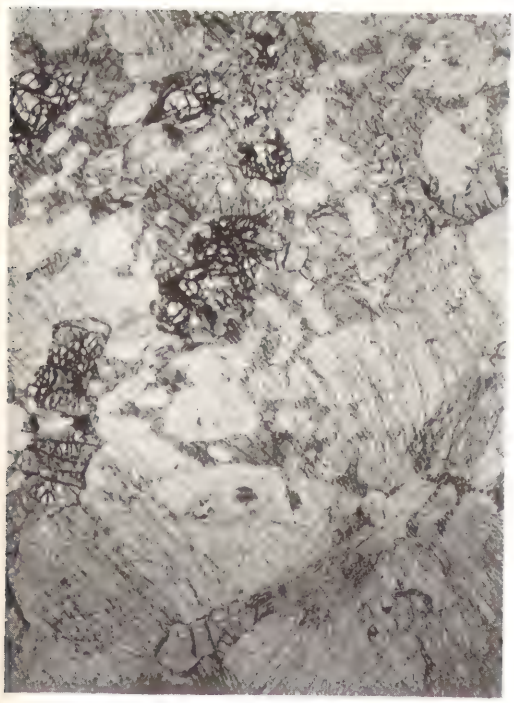
4

The same as 3. Crossed nicols (X 12).

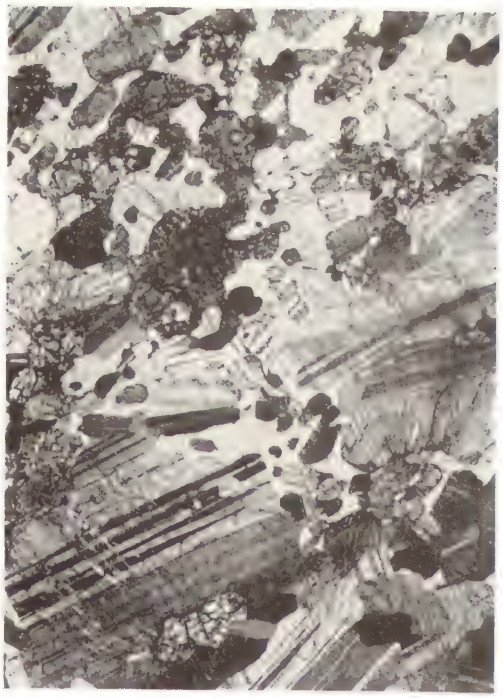
1



2



3



4

PLATE IX

Danau Formation: intrusive ophiolites

1

H. 23. Dunite. A few grains of olivine in a fibro-lamellar mass of antigorite-serpentine. S. coast of Manawali Island, N. of Bengkoka Peninsula. Crossed nicols (X 19).

2

R. 44. Dunite, saussurite-bearing. Irregular patches of saussurite (black) in partially serpentinised (chrysotile) olivine. Blantian River, SE. coast of B.N.B. Crossed nicols (X 12).

3

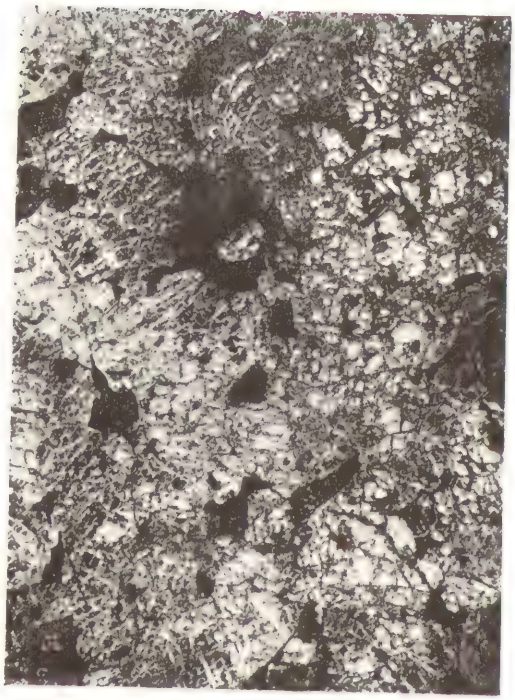
Nh. 461. Serpentine-mylonite. S.Makadau, N. of Kampong Numulat. Interior of B.N.B. Crossed nicols (X 20).

4

J. 227. Dunite-serpentine, showing fibrous texture of chrysotile. S.Diwata near Lahad Datu, E. coast of B.N.B. Crossed nicols (X 16).

1

2



3

4

PLATE X

Danau Formation: ophiolites and associated rocks

1

R. 35. Harzburgitic serpentine, saussurite-bearing. Mesh texture of antigorite-serpentine. Black patches are saussurite. Blantian River. Crossed nicols (X 16).

2

Nh. 192. Nephrite; nematoblastic felt of actinolite shreds and needles. 6 km. to the ENE. of Kota Belud, NW. coast of B.N.B. Crossed nicols (X 16).

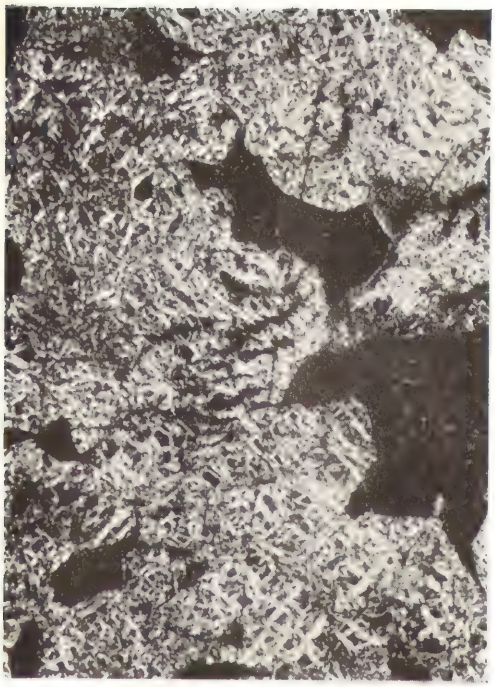
3

R. 6. Pumpellyite-chlorite vein in ophiolitic breccia. Radiating fibres of pumpellyite. The light-coloured streaks are formed by delessite (grey), calcite and zeolites (white). Blantian River, SE. coast of B.N.B. Without analyser (X 18).

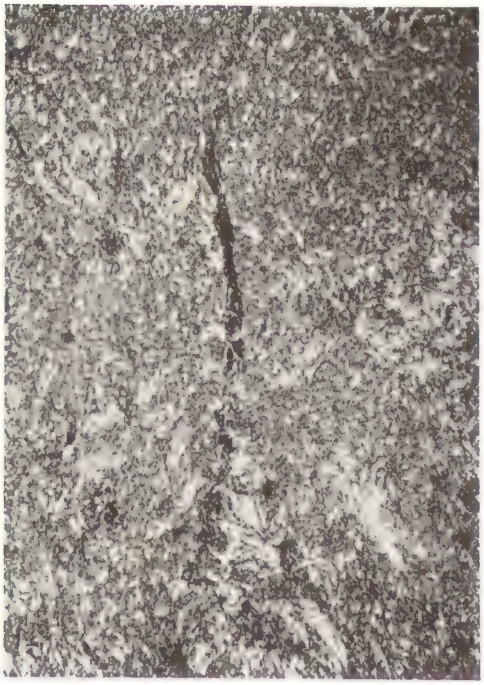
4

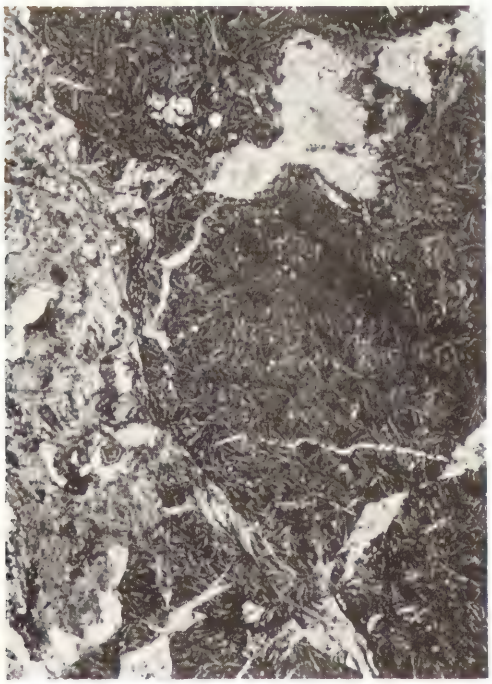
St. 184. Sub-ophitic diabase. The plagioclase laths are turbid. White: secondary albite. In places, micro-pegmatitic intergrowth of plagioclase with branching augite crystals (upper right-hand corner). Segama River, Dent Peninsula, E. coast of B.N.B. Crossed nicols (X 10).

1



2





3

4

PLATE XI

Danau Formation: extrusive ophiolites

1

Nh. 70. Albite-diabase. Intersertal texture. Albite laths in a quasi-isotropic matrix of chlorite. The rock is invaded by calcite in irregular streaks and nests. Mafics completely altered. Kudat Bay, N. coast of B.N.B. Crossed nicols (X 10).

2

Wk. 56. Porphyritic diabase. Plagioclase phenocrysts completely altered to a micaceous felt. Groundmass composed of sericitised plagioclase microlites and minute granules of haematite. Tungku River, S. coast of Dent Peninsula. Without analyser (X 12).

3

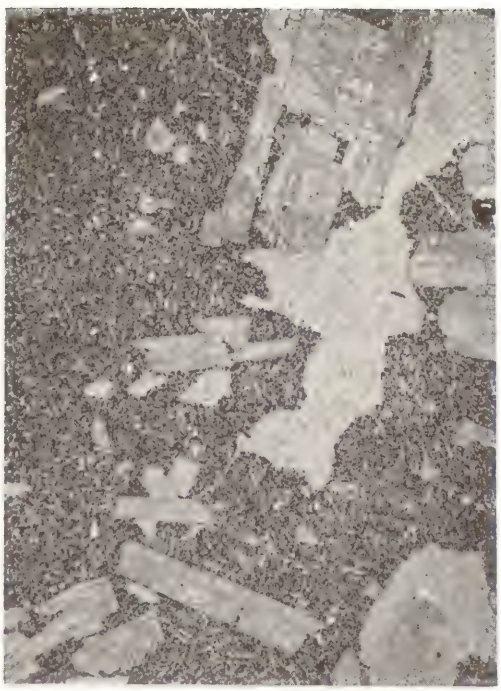
H. 113. Doleritic basalt, sub-ophitic-intersertal texture. Laths of plagioclase very fresh, often zoned, core 65%, border 30% An; less augite, dark-brown glass with ilmenite skeletons. Telok Gapas, N. of Paitan Bay, W. coast of Bengkoka Peninsula. Crossed nicols (X 12).

4

H. 19 Intersertal basalt. Needles of fresh plagioclase $\pm$65% An. Augite in feathery crystals and small granules, small amount of dark-brown glass. W. coast of Banggi Island, S.Limbuak. Without analyser (X 12).

1

2



3

4

PLATE XII

Danau Formation: extrusive ophiolites

1

Wk. 1. Porphyritic and amygdaloidal basalt. Texture hyalopilitic-vesicular. Phenocrysts of glassy plagioclase (65%–70% An) and of augite. Groundmass: dark-brown glass with ilmenite skeleton-crystals, plagioclase needles and augite grains. Amygdules completely filled or marginally coated with minute fibres of pumpellyite. Kuamut River, tributary of Kinabatangan. Without analyser (X 12).

2

H. 80. Amygdaloidal diabase, pilotaxitic texture. Plagioclase laths with a central rod of minute chlorite and titanite granules. Interstices with titaniferous augite and ilmenite. Amygdules filled with calcite, coated with a narrow rim of light-green chlorite. Balayayong River, Taritipan, SE. corner of Marudu Bay. Crossed nicols (X 19).

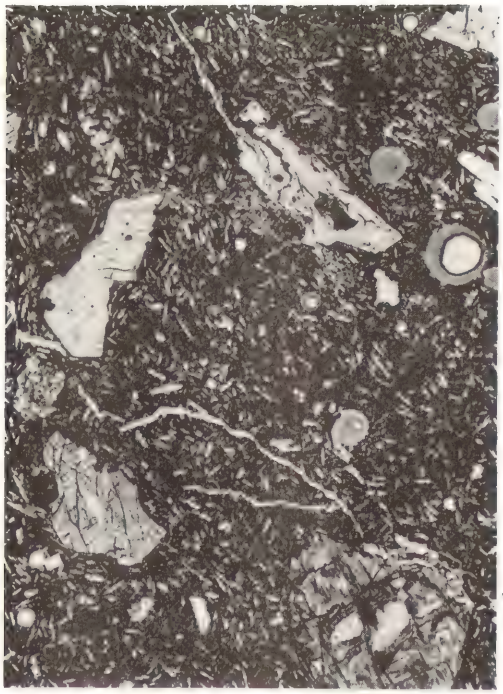
3

R. 26. Amygdaloidal spilite, pilotaxitic-hyalopilitic texture. Albite needles with a central rod of titanite and chlorite in a spongy mass of albite, sprinkled with skeletons of ilmenite and granules of calcite and titanite. Small patches of bowlingite and infiltrations of calcite. Amygdules filled with calcite. Blantian River, SE. coast of B.N.B. Crossed nicols (X 16).

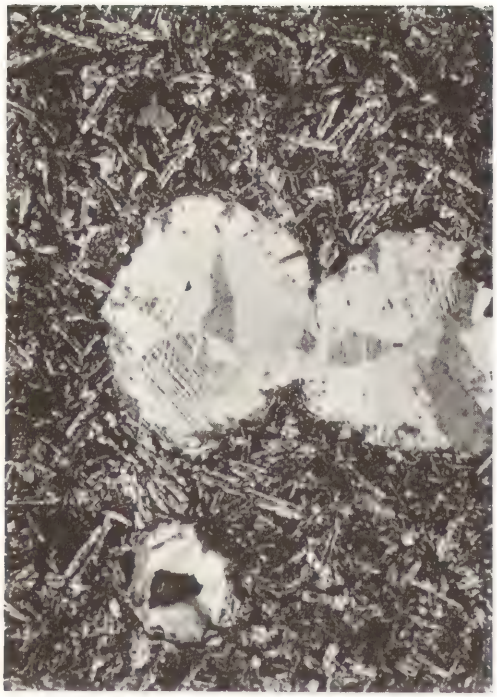
4

J. 150. Amygdaloidal spilite. Felty mass of minute plagioclase needles and grains of augite and titanite. Amygdules filled with delessite and albite. Batu Tatak on Segama River, Dent Peninsula, E. coast of B.N.B. Without analyser (X 12).

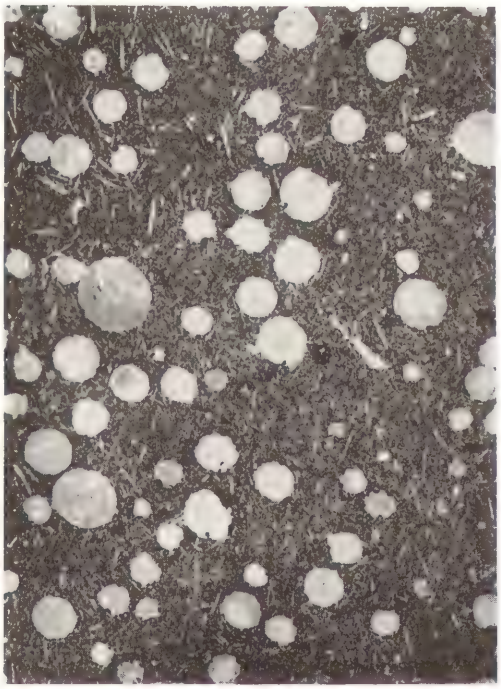
1



2



3



4

PLATE XIII

Danau Formation: extrusive ophiolites and their tuffs

1

St. 189. Keratophyre (= aegirine-soda-trachyte). Trachytic texture. Feldspar laths turbid (brown dust). Small branching crystals of aegirine embedded in a micro-felt of hornblende needles (visible only with high magnification). Pulau Ta in Segama River, Dent Peninsula. Crossed nicols (X 12).

2

Nh. 144. Lithic spilite-tuff. Fragments of spilite cemented by calcite, quartz, chlorite and limonite. Kudat Peninsula E. coast, W. of Langkom. Without analyser (X 19).

3

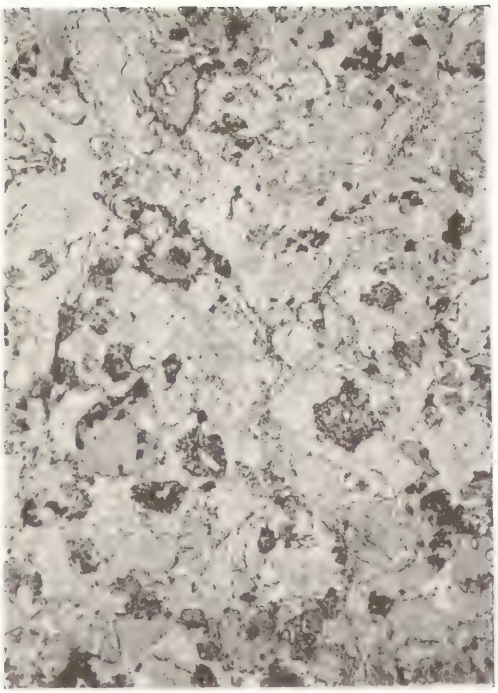
Nh. 397. Lithic spilitic-calcareous tuffite. S.Liwagu Kuananan. Interior of B.N.B. Without analyser (X 16).

4

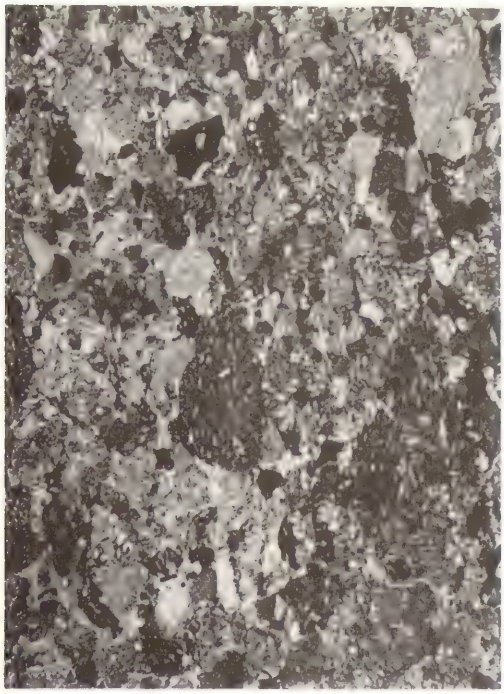
Wk. 81. Metamorphic lithic spilite-breccia. Fragment of spilite with albite needles and a large phenocryst of albite (right-hand border), partially replaced by calcite, surrounded by a micro-nematoblastic aggregate of blue-green hornblende. Block from S.Kadamayan (upper Tampasuk) near Kiau, S.W. slope of Gg. Kinabalu. Without analyser (X 19).

1

2



3



4

PLATE XIV

Crystalline schists

1

L. 97. Actinolite-talc-chlorite-schist. S.Telewas, right-hand tributary of Segama River, Dent Peninsula. Crossed nicols (X 12).

2

L. 135a. Actinolite-muscovite-schist, garnet and clinozoisite-bearing, composed of 50% grey-blue actinolite and of quartz, muscovite and clinozoisite in equal amounts. Accessory rutile and clinochlore (visible only with a high-powered lens). Lower course of Segama River, Dent Peninsula. Crossed nicols (X 19).

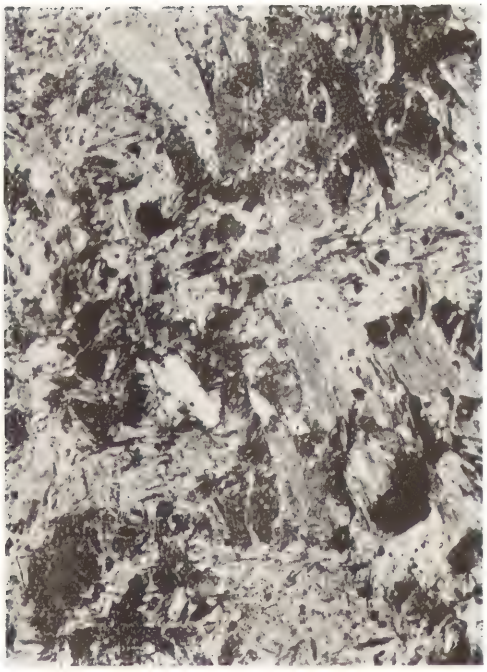
3

L. 194b. Plagioclase-hornblende-hornfels. Equal amounts of fresh plagioclase, generally not twinned, feebly zoned (30%–40% An), and green common hornblende. Accessory ilmenite. Pronounced granoblastic texture. P. Tanna in Darvel Bay. S. of Lahad Datu, E. coast of B.N.B. Crossed nicols (X 20).

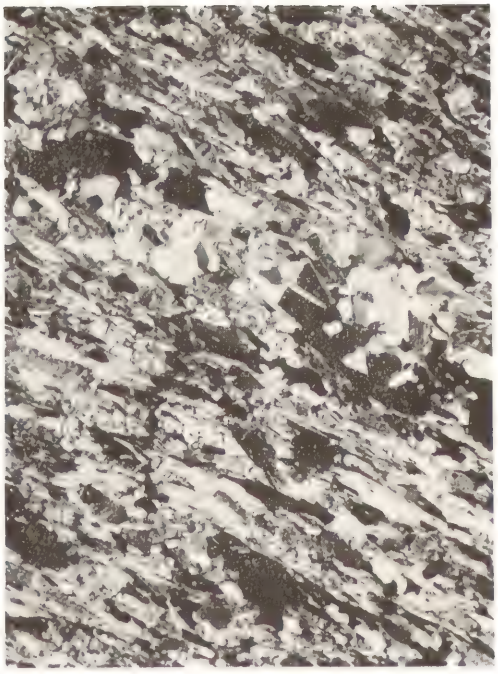
4

Wk. 46. Amphibolite. Patches of micro-diablastic aggregate of greenish-blue hornblende, and plagioclase, surrounded by indistinctly granoblastic green hornblende (grey), skeletons of ilmenite crystals (black) and a few grains of plagioclase (white). S.Mungkuou, S. coast of Dent Peninsula. Without analyser (X 12).

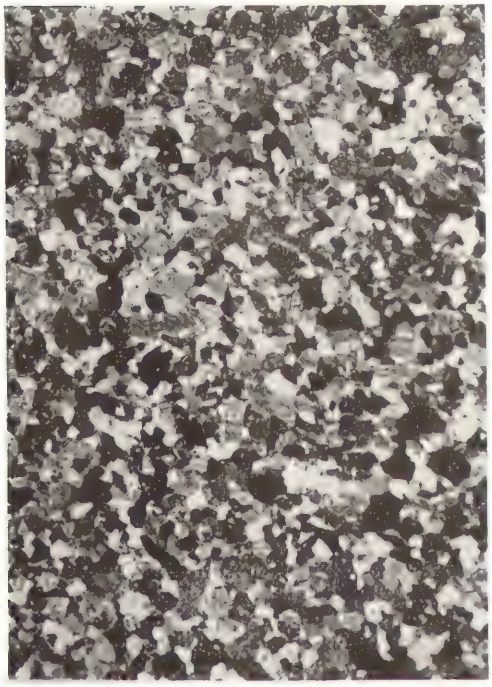
1



2



3



4

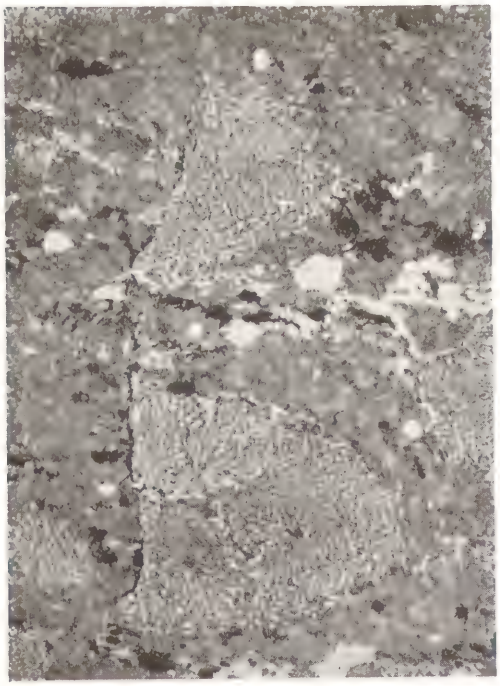


PLATE XV

Crystalline schists

1

Wk. 34. Carinthine-eclogite. Garnet xenoblasts with micro- to cryptocrystalline rims and cracks of kelyphite (hornblende-plagioclase intergrowth) in a grano- to nemato-blastic aggregate of light grey-bluish omphacite and olive-green carinthine-hornblende. S.Mungkuou, S. coast of Dent Peninsula. Without analyser (X 16).

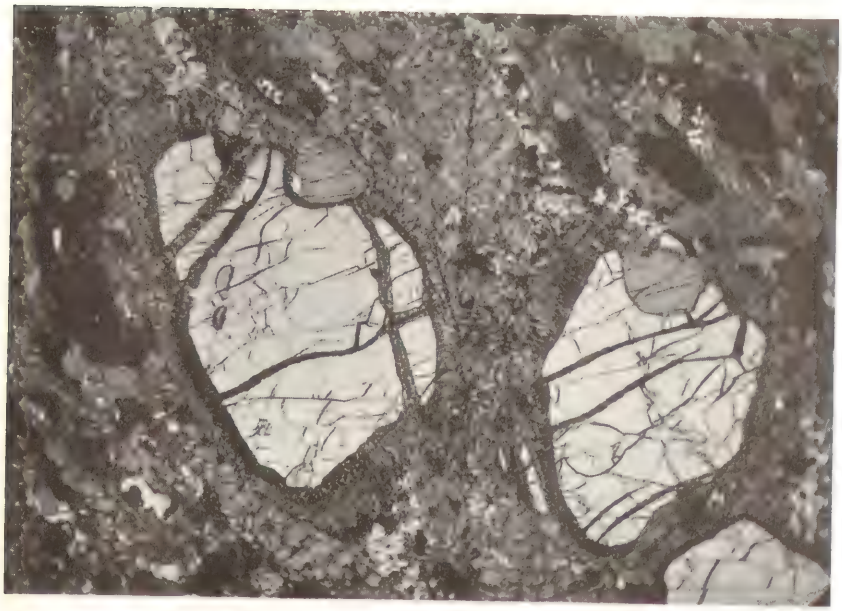
2

Wk. 54. Feldspathised carinthine-eclogite. Rounded porphyroblasts of garnet with cracks and narrow cryptocrystalline kelyphitic rims, more elongated xenoblasts of olive-green carinthine-hornblende, clouded by ilmenite microlites. White streaks: microgranoblastic fresh untwinned plagioclase. Grey streaks: aggregate of small fragments of hornblende and omphacite. S.Pungulupi, tributary of S.Tungku, S. coast of Dent Peninsula. Without analyser (X 12).

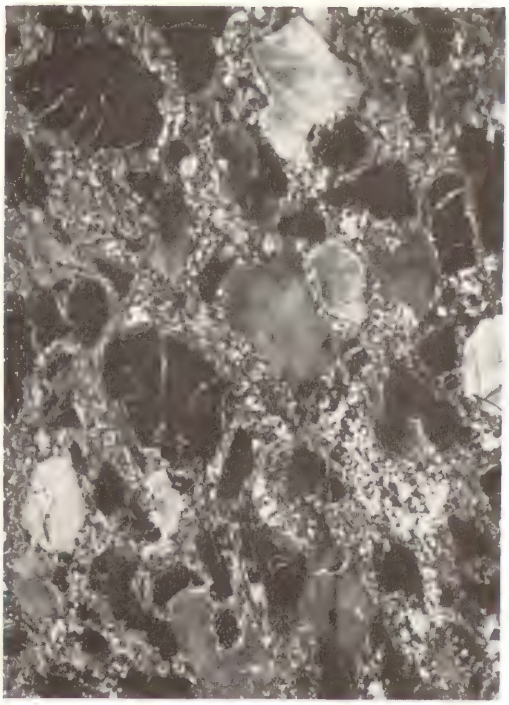
3

The same as 2, with crossed nicols (X 12). The cataclastic texture is conspicuous.

1



2



3

PLATE XVI

Gunong Kinabalu (quartz-monzonitic intrusive body)

1

View from Low's Peak (4,100 m.) towards the central abyss and the eastern summits.

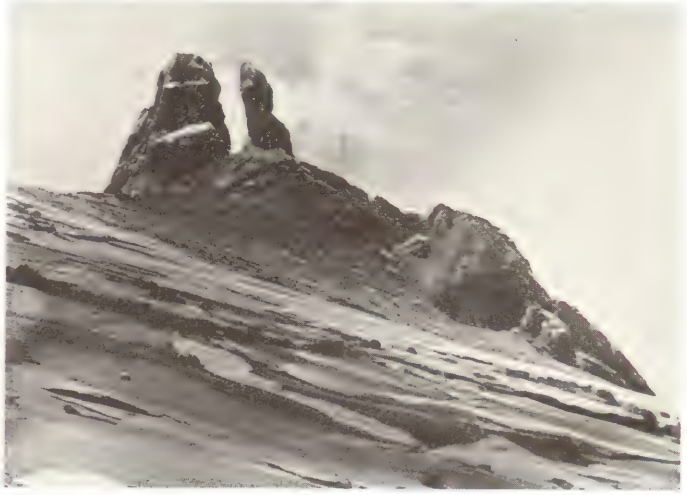
2

Gunong Kinabalu (background) and Gunong Nungkok (centre) as seen from the hills above Bongol (WNW. of Kinabalu).

3

Summit plateau and pinnacles. Note the platy structure in the foreground. The light-coloured slabs consist of biotite-diopside-granodiorite-porphyry resting upon hornblende-micro-quartz-monzonite containing quartz-dioritic inclusions, rich in hornblende.

2



3

PLATE XVII

River scenery

1

23 m. high cataract in the head-waters of S.Tabin Besar (Dent Peninsula).

2

Wossoi Mayo in S.Kuamut between Kg. Lonod and Kg. Kasuyon. S.Kuamut pouring over an 8 m. high sandstone scarp face of the Te_5-f formation.

3

Shooting the rapids (*giram*) of S.Bangan (tributary of S.Milian). Outcrop of the well-bedded shale-sandstone series of Te_5-f age.

4

Hauling the dug-out canoes through the rapids (*giram*) of S.Kuamut. Poorly bedded, hard sandstone boulders of Te_{1-4} age.

1

2

3

4

PLATE XVIII

1

Sandstone slab of the well-bedded shale-sandstone series of Te_5-f age, showing ripple marks. S.Sapulut (southern-central part of North Borneo).

2

Salty mud flowing down the slopes of a mud-volcano into dying jungle. Area between Segama River and Dewhurst Bay.

3

Scenery in S.Tabin Besar (Dent Peninsula).

4

Batu Punggul in S.Sapulut (southern-central part of North Borneo). Coral limestone cliff of Te_{1-3} age.

1

2

3

4

PLATE XIX

1

Concretion in sandstone of Te age, N.E coast.

2

Vent of mud-volcano on P. Lihaiman with mud-flow destroying coconut plantation.

3

Small mud-cone in the centre of the large Tagai Rasang (Kinabatangan area).

4

Salt-water and gas-seep in the jungle of lower Segama-Kinabatangan area. Brackish-water type vegetation.

1

2

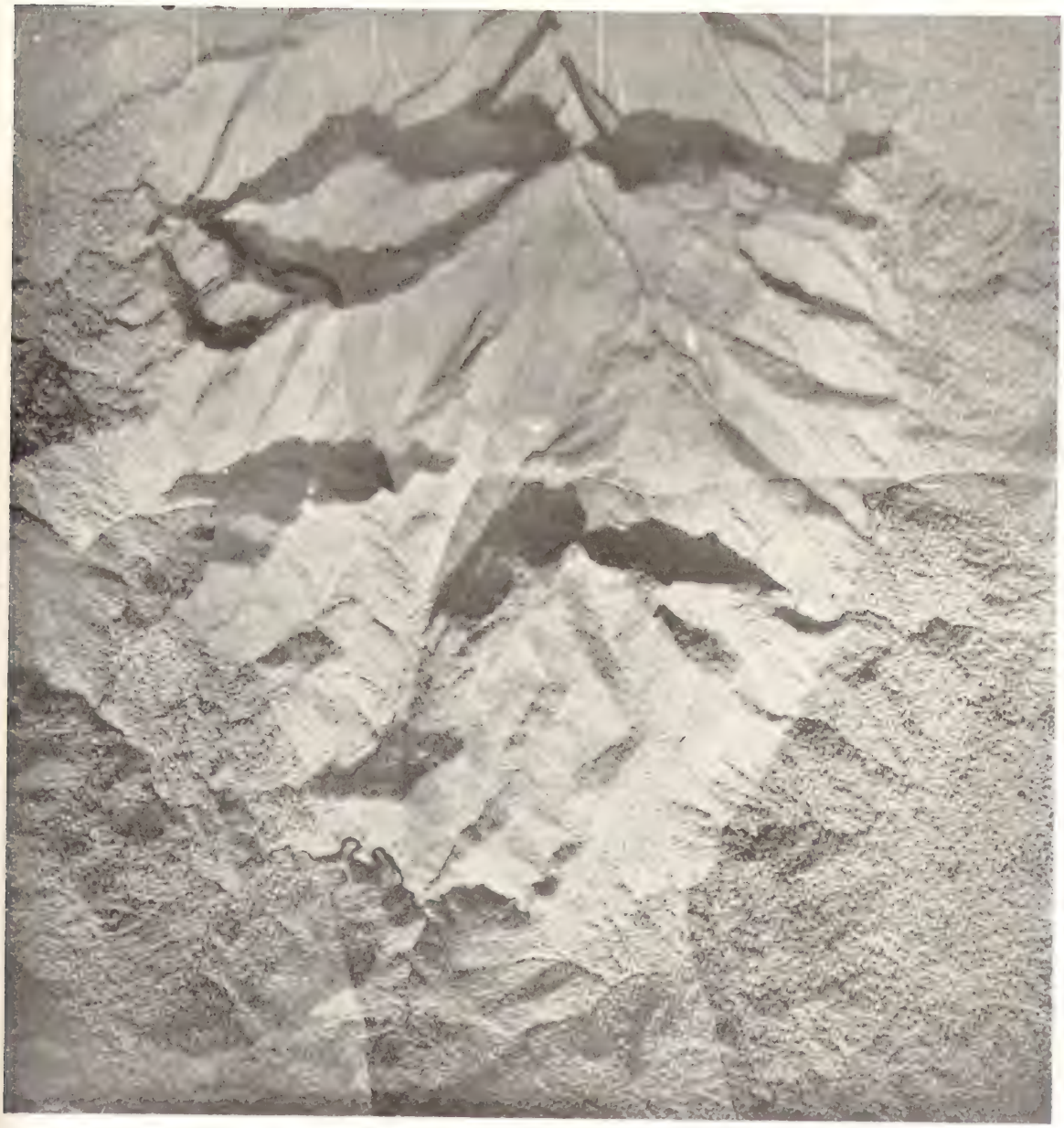
3

4

PLATE XX

Gunong Rara

Aerial view (photo-mosaic) of Gunong Rara, 26 km. SSW. of Tangkulap (Milian area), between the head-waters of S.Sinoa (tributary of the Milian; left-hand part of the picture) and S.Nambunawon (tributary of S.Kuamut; right-hand part of the picture). The position of the mountain is seen on Enclosure VII. Scale of picture approx. 1:50,000; top of picture points towards ESE. The remarkable unexplored mountain massif of Gg. Rara has a perfect elliptical shape and the top towers at least 1,500 m. above the adjacent valleys. The nature of the rock became evident from boulders found in S.Sinoa (Wk. 5–9 in Appendix I). Gg. Rara appears to represent a plutonic body of granodioritic composition morphologically and geologically similar to that of Gg. Kinabalu. The tall jungle in the gently undulating foothills, formed by Tertiary sediments, is clearly distinguished from the scrubby vegetation found on the plutonic body. The line of contact between the intrusive and the sedimentary rocks is pronounced, especially in the right-hand part of the picture. Gg. Rara is known to the natives of Kg. Kuamut and, according to information given by them, the mountain is very difficult of access.



Bibliography

A. BRITISH NORTH BORNEO

AGAMENNONE, G. 1898. I terremoti nell'isola di Labuan (Borneo) del 21 settembre 1897. Rendiconti R. Ac. dei Lincei, Vol. VII, Roma.

COX, L. R. 1948. Neogene mollusca from the Dent Peninsula, British North Borneo. Schweiz. Palaeontol. Abhandl. Vol. 66, Basel.

DIESELDORFF, A. 1906. Neue Manganerz-Vorkommen in Britisch Nord-Borneo. Zeitschr. prakt. Geol. 14. Jahrg.

FELIX, J. 1921. Fossile Anthozoen von Borneo. Palaeontologie von Timor, Lief. IX, Abhandl. XV. Stuttgart.

GERTH, H. 1923. Die Anthozoenfauna des Jungtertiärs von Borneo. Sammlungen des Geol. Reichsmuseums, Leiden, Ser. I, Bd. X.

HANDBOOK of the State of British North Borneo. 1921. British North Borneo Chartered Company.

HATTON, F. 1882. Diary during a mineral exploration journey up the Labuk river and overland to Kudat. British North Borneo Co.

1886. North Borneo: Explorations and adventures on the Equator, London.

JENNINGS, A. V. 1888. Note on the orbitoidal limestone of North Borneo. Geol. Mag., New Ser., Dec. III. Vol. V.

MOTLEY, J. 1853. Report on the geological phenomena of the Island of Labuan. Quart. Journ. Geol. Soc.

NEWTON, Bullen R. 1897. On a Jurassic lamellibranch and some other associated fossils from the Sarawak-River limestones of Borneo, with a sketch of the Mesozoic fauna of the island. Geol. Mag., New Ser., Dec. IV., Vol. IV.

and HOLLAND, R. 1899. On some Tertiary foraminifera from Borneo. Annals and Magaz. of Nat. Hist. (7) III.

PILZ, R. 1913. Geologische Studien in Britisch Nord Borneo. VI. Jahresber. Freiberger Geol. Ges.

1914. Einige Bemerkungen zur Genesis der Huelvaner Kies und Manganerzlagerstätten. Zeitschr. prakt. Geol. 22. Jahrg.

REINHARD, M. 1924. Contributions to the Physiography and Geology of the South-East Coast of British North Borneo. Geog. Journ.

RUTTEN, L. 1915. Studien über Foraminiferen aus Ost-Asien. 9. Tertiäre Foraminiferen von den Inseln Balambangan und Banguey, nördl. von Borneo. Sammlungen Geol. Reichsmuseums, Leiden, Ser. I, Bd. X.

1921. Over den ouderdom der tertiaire, oliehoudende afzettingen van Klias-schiereiland en Poeloe Laboean (Noordwest-Borneo). Kon. Akad. van Wetenschappen, Amsterdam, Verslag Wis- en Natuurk. Afd., Deel XXIX.

1922. On the age of the tertiaire oil-bearing deposits of the peninsula of Klias and Pulu Labuan (N.W. Borneo). Kon. Akad. van Wetenschappen, Amsterdam, Proceedings Vol. XXIII, No. 8, Sect. of Sciences. (Translation of the preceding paper.)

1925a. Over fossielhoudende tertiaire Kalksteenen uit Britisch Noord Borneo. Verhandel. Geol. Mijnbouwk. Genootschap van Nederl. en Koloniën, Geol. Ser. Vol. VIII.

1925b. Tertiary Rocks from North-Western British Borneo and from Berau (E. Borneo). Kon. Akad. van Wetenschappen, Amsterdam. Proceedings, Vol. XXVIII, No. 7, Sect. of Sciences.

RUTTEN, M. G. 1948. On the contemporaneous occurrence of Lepidocyclina and Discocyclina in Northern Borneo. Geologie en Mijnbouw, Nieuwe Serie, 10e jaargang.

RUTTER, Owen. 1922. British North Borneo. An account of its history, resources and native tribes. London, Constable & Co.

SCHMIDT, C. 1901. Observations géologiques à Sumatra et à Bornéo. Bull. Soc. géol. de France, 4ème série, tome I.

1904. Ueber die Geologie von Nordwest-Borneo und eine daselbst entstandene "Neue Insel". Gerlands Beiträge zur Geophysik, Bd. VII, Heft 1.

SKERTCHLEY, S. B. J. 1897. Report on the Segama Gold Field, 1889. British North Borneo Co.

STIGAND, J. A. 1911. Some contributions to the physiography and hydrography of North-East Borneo. The Geog. Journ.

VERSLAG der Commissie tot uitzetting op het terrein van de tusschen het Nederlandsche gebied en Britisch Noord-Borneo vastgestelde grens. 1913. 's-Gravenhage, Martinus Nijhoff.

WANNER, J. 1921. Beiträge zur Geologie und Geographie von Nordost-Borneo. Ergebnisse einer von Dr. K. Stamm in den Jahren 1913 und 1914 ausgeführten Reise, nach seinen hinterlassenen Aufzeichnungen und Sammlungen zusammengestellt und unter Mitwirkung von Prof. Dr. H. Bücking bearbeitet. Neues Jahrb. Min., Geol & Päläont. Beil. Bd. XLV.

WENK, E. 1946. Gunong Kinabalu, der Viertausender von Borneo. Die Alpen, Jahrg. 1946, Heft 12.

WOODS, J. E. T. 1885. The Borneo Coalfields. Nature.

WORTH, W. J. 1940. Notes on mineral research in North Borneo. The Asiatic Review, London, Vol. XXXVI, No. 126.

YABE, H. 1918. Notes on a Carpenteria-limestone from Brit. North Borneo. Sci. Rep. Tôhoku Imp. Univ. Sendai, 2nd Ser. (Geology), Vol. V, No. 1.

and HANZAWA, S. 1925. A Lepidocyclina-limestone from Klias Peninsula, B.N. Borneo. Verhand. Geol. Mijnbouwk. Genootsch. van Nederl. en Koloniën, Vol. VIII.

1926. A foraminiferal limestone with a questionable fauna from Klias Peninsula, British North Borneo. Sci. Rep. Tôhoku Imp. Univ. Sendai, 2nd Ser. (Geology), Vol. IX.

B. THE EAST INDIES

BEMMELEN, R. W. VAN. 1939. De geologie van het westelijke en zuidelijke deel van de Westerafdeeling van Borneo. Jaarboek van het Mijnwezen in Nederl. Indië, 68. Jaargang, Verhandelingen.

BROUWER, H. A. 1925. The Geology of the Netherlands East Indies. New York.

BRUGGEN, G. TER. 1935. De Eocene Fyllietformatie in Centraal-Borneo. Thesis, Delft.

DOUVILLÉ, H. 1905. Les foraminifères dans le Tertiaire de Bornéo. Bull. Soc. Géol. de France, 4e Série, Vol. V.

ES, L. J. C. VAN. 1920. De tektoniek als basis voor de opsporing van ertsen en fossiele brandstoffen. Algem. Ing. Congres, Batavia, 5. sect.

HEIM, Arn. 1942. Lebende Diapire in den südöstlichen Molukken. Eclogae Geol. Helvet., Vol. 35.

KOOLHOVEN, W. C. B. 1935. Het primaire voorkomen van den Zuid-Borneo diamant. Verhand. Geol. Mijnbouwk. Genootsch. voor Nederland en Koloniën, Geol. Ser., Vol. XI.

KROEKEL, F. 1923. Gesteine aus dem Gebiet des Boeloenganflusses im nordöstlichen Borneo. Sammlungen des Geol. Reichsmuseums in Leiden, Ser. I, Bd. X.

KUENEN, Ph. H. 1935. Geological interpretation of the bathymetrical results. Part I of Vol. V. Geological results. The Snellius expedition in the eastern part of the Netherlands East Indies, 1929–1930. Leiden.

LEUPOLD, W., and VAN DER VLERK, I. M. 1931. The Tertiary. Leidsche Geol. Mededeel. Deel V. Feestbundel K. Martin.

MOLENGRAAFF, G. A. F. 1900. Borneo-Expeditie. Geologische verkenningstochten in Centraal-Borneo (1893–1894). With atlas. Leiden & Amsterdam.

1902. Borneo Expedition. Geological explorations in Central Borneo (1893–1894). Leyden & Amsterdam. (Translation of the preceding publication.)

1909. On oceanic deep-sea deposits of Central Borneo. Kon. Akad. van Wetenschappen, Amsterdam, Proceedings, Vol. XII, Sect. of Sciences.

1914. Hoofdtrekken der geologie van Oost-Borneo naar aanleiding der reizen van Prof. A. W. Nieuwenhuis en anderen. Verhand. Geol. Mijnbouwk. Genootsch. voor Nederl. & Koloniën, Geol. Sect. Deel I.

1922. De geologie der zeeën van den O. I. Archipel. Kon. Nederl. Aardr. Genootsch.: De zeeën van Nederl. Oost-Indië.

MUNNIKS DE JONGH, W. D. 1913. Aantekeningen over de Tidoeng'sche Landen (Res. Z. en O. Afd. van Borneo). Jaarb. Mijnwezen in Nederl. Indië, 42. Jaarg. Verhandel.

NIETHAMMER, G. 1909. Die Eruptivgesteine von Loh oelo auf Java. Tscherm. Min. Petr. Mitteil. Bd. 28.

POSEWITZ, Th. 1889. Borneo. Entdeckungsreisen und Untersuchungen. Gegenwärtiger Stand der geol. Kentnisse. Verbreitung der nutzbaren Mineralien. Berlin.

1892. Borneo: Its Geology and Mineral Resources. Translated from the German by F. H. Hatch, Stanford. (Translation of the preceding book.)

ROEVER, W. P. DE. 1940. Geological investigations in the south-western Moetis Region (Netherlands Timor). Thesis. Amsterdam.

1947. Occurrences of the mineral pumpellyite in Eastern Borneo. Bull. Bureau of Mines and the Geol. Survey in Indonesia, Vol. I, No. 1.

ROOTHAAN, H. Ph. 1928. Geologische en petrografische schets der Talaud- en Nanoesa-eilanden (NE.-Celebes). Jaarb. Mijnwezen Nederl. Indië., Vol. 54 (voor 1925), Verhand. 2. Deel.

RUTTEN, L. M. R. 1927. Voordrachten over de geologie van Nederlandsch Oost Indië. Groningen, Den Haag.

RUTTEN, M. G. 1947. De gesteenten der Midden Oost Borneo expeditie 1925. Geogr. en Geol. Mededeelingen. Publicaties Geogr. en Min. Geol. Instit. Rijksuniv. Utrecht. Physiogr.-Geol. Reeks, Ser. II, No. 9.

SCHNEEBERGER, W. F. 1945. The Keraijan-Kalabit highland of Central North-East Borneo. Geog. Rev., Vol. XXXV, No. 4.

UMBGROVE, J. H. F. 1934. The relation between geology and gravity field in the East Indian Archipelago. Gravity expeditions at sea, 1923–1932, Vol. II, by F. A. Vening Meinesz. Delft.

1938. Geological history of the East Indies. Bull. Am. Assoc. Petroleum Geol., Vol. 22.

VLERK, I. M. VAN DER, and UMBGROVE, J. H. F. 1927, Tertiaire Gidsforaminiferen van Nederlandsch Oost Indië. Wetensch. Mededeel., No. 6, Dienst van den Mijnbouw.

WILLEMS, H. W. V. 1940. On the magmatic provinces in the Netherlands East Indies. Verhand. Geol.-Mijnbouwk. Genootsch. voor Nederl. en Koloniën, Geol. Serie, Deel XII.

ZEIJELMANS VAN EMMICHOVEN, C. P. A., and UBACHS, J. G. H. 1936. Beschouwingen over den veronderstelden eoceenen ouderdom van de geheele " Oude Leiformatie " in Centraal Borneo. De Ingenieur in Nederl. Indië, Vol. IV.

ZEIJELMANS VAN EMMICHOVEN, C. P. A. 1938. Korte schets van de geologie van Centraal Borneo. De Ingenieur in Nederl. Indië, Vol. IV.

1939. De geologie van het centrale en oostelijke deel van de westerafdeeling van Borneo. Jaarb. Mijnwezen in Nederl. Indië, 68e Jaargang, Verhand. Batavia.

C. GENERAL GEOLOGY AND PETROLOGY

BESKOW, G. 1929. Södra Storfjället im südl. Lappland. Eine petr. und geol. Studie im zentralen Teil des skandinavischen Hochgebirges. Sveriges geol. Undersökning. Ser. C. Avhandl. och uppsatser., No. 350, Årsbok 21, Stockholm.

BORLOZ, A. 1924. Contributions à l'étude des plagioclases des roches d'épanchement. Genève, thèse de doctorat, No. 744.

BOWEN, NORMAN L. 1947. Magmas. Papers from the Geophysical Lab., Carnegie Inst., Washington, No. 1088.

BURRI, C., and NIGGLI, P. 1945. Die jungen Eruptivgesteine des mediterranen Orogens. I. Einleitung. Die Ophiolithe. Allgemeines über das Verhalten basischer Magmen. Berechnungsmethoden. No. 3 der Publikationen der Stiftung "Vulkaninstitut Immanuel Friedlaender", Zürich.

DAVIS, E. F. 1918. The radiolarian cherts of the Franciscan Group. University of California Publications, Bull. of the Dep. of Geol., Vol. 11.

DEWEY, H., and FLETT, J. S. 1911. On some British Pillow-lavas and the rocks associated with them. Geol. Mag. New Ser., Dec. V, Vol. VIII, pp. 202–209 and 241–248.

ELLIS, E. 1948. On the delimitation of Diorite and Gabbro and related rocks. Min. Mag., Vol. 28.

ESKOLA, P., VUORISTO, U., and RANKAMA, K. 1935. An experimental illustration of the spilite reaction. Soc. géol. de Finlande, No. 9.

GILLULY, J. 1935. Keratophyres of Eastern Oregon and the Spilite Problem. Am. Journ. Sci., Vol. XXIX.

GLASS, J. J., and SHALLER, W. T. 1939. Inesite. American Mineralogist, Vol. 24.

HOMMA, F. 1932. Ueber das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten mit Hilfe des Universaldrehtisches. Schweiz. Min. Petr. Mitteil. Bd. XII.

KOEHLER, A. 1942. Die Abhängigkeit der Plagioklasoptik vom vorausgegangenen Wärmeverhalten. Zeitschr. Krist. Abt. B, Bd. 53.

KROKSTROEM, T. 1932. On the ophitic texture and the order of crystallization in basaltic magmas. Bull. Geol. Inst. Upsala., Vol. XXIV.

LARSEN, E. S., and IRVING, J. 1937. The amphiboles, in: E. S. Larsen, J. Irving, F. A. Gonyer and E. S. Larsen, 3rd. Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region. American Mineralogist, Vol. 22.

LEHMANN, E. 1941. Eruptivgesteine und Eisenerze im Mittel-und Oberdevon der Lahnmulde. Wetzlar.

LOTTI, B. 1886. Descrizione geologica dell'Isola d'Elba. Roma.

NIGGLI, P. 1919. Petrographische Provinzen der Schweiz. Vierteljahrsschrift Naturf. Ges. Zürich, Bd. 64.

1931. Die quantitative mineralogische Klassifikation der Eruptivgesteine. Schweiz. Min. Petr. Mitteil. Bd. 11.

1936a. Ueber Molekularnormen zur Gesteinsberechnung. Schweiz. Min. Petr. Mitteil., Bd. 16.

1936b. Die Magmentypen. Schweiz. Min. Petr. Mitteil., Bd. 16.

OVEREEM, M. J. A. VAN. 1948. A section through the Dalformation. A contribution to the geology of Dalsland, SW. Sweden. Leiden.

PALACHE, CH., and VASSAR, H. E. 1925. Some minerals of the Keweenawan Copper deposits: Pumpellyite, a new mineral; sericite, saponite. American Mineralogist, Vol. 10.

PANTENELLI, D. 1883. Diaspri elbani. Processi verbali Soc. toscana di Sc. nat., Vol. III.

PHEMISTER, J. 1934. Zoning in plagioclase felspar. Min. Mag., Vol. XXIII.

QUITZOW, H. W. 1936. Pumpellyit, ein häufiges Hydrothermal-und Sekundärmineral in basischen Gesteinen. Zentralbl. Min. Geol. Pal. Abt. A.

REINHARD, M. 1931. Universaldrehtischmethoden. Basel, B. Wepf und Co.

RITTMANN, A. 1929. Die Zonenmethode. Schweiz. Min. Petr. Mitteil., Bd. 9.

1936. Vulkane und ihre Tätigkeit. Stuttgart.

1944. Vulcani. Attività e genesi. Napoli (enlarged edition of the preceding book).

SPAENHAUER, F. 1933. Ueber das Ergebnis von Messungen an synthetischen Plagioklasen mit Hilfe des Universaldrehtisches. Schweiz. Min. Petr. Mitteil., Bd. 13.

STAUB, R. 1928. Der Bewegungsmechanismus der Erde. Berlin.

STEINMANN, G. 1897. Geologische Beobachtungen in den Alpen. I. Das Alter der Bündnerschiefer. Berichte naturf. Ges. Freiburg i./B. Bd. X.

1905. Geologische Beobachtungen in den Alpen. II. Die Schardt'sche Ueberfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolitischen Massengesteine. Berichte naturf. Ges. Freiburg i./B. Bd. XVI.

STEINMANN, G. 1926. Die ophiolitischen Zonen in den mediterranen Kettengebirgen. C. R. XIVe Congrès intern. Géol.

TEALL, J. J. H. 1895. On greenstones associated with Radiolarian Cherts. Trans. Roy. Geol. Soc. Cornwall, Vol. XI.

TERCIER, J. 1939. Dépôts marins actuels et séries géologiques. Eclogae Geol. Helvet., Vol. 32.

WARREN, B. E. 1930. The crystal structure and chemical composition of the monoclinic amphiboles. Zeitschr. Kristall. Vol. 72.

WENK, E. 1945a. Kritischer Vergleich von simultan nach der Drehtisch- und Immersionsmethode ausgeführten Anorthitbestimmungen an Plagioklasen. With English summary. Schweiz. Min. Petr. Mitteil. Bd. XXV.

1945b. Die Koexistenzbeziehungen zwischen Hornblende, Biotit und Feldspaten und die Bedeutung der oscillierenden Zonarstruktur. Schweiz. Min. Petr. Mitteil. Bd. XXV.

WENK, E. 1948. Beziehungen zwishen normativem und modalem Anorthitgehalt in Eruptivgesteinen und kristallinen Schiefern. Schweiz. Min. Petr. Mitteil. Bd. 28.

WENTWORTH, C. K., and WILLIAMS, H. 1930–1932. The classification and terminology of the pyroclastic rocks. Bull. Nat. Research Council. Rep. Com. on Sedimentation, No. 89.

D. MAPS

The State of North Borneo. 1934. Scale 8 miles to an inch. Printed by F.M.S. Surveys, No. 59, 1935.

E. LIST OF UNPUBLISHED REPORTS CONSULTED

I. Reports made on behalf of the Nederlandsche Koloniale Petroleum Maatschappij.

Copies of these reports are deposited at the Mineralogical Institute of the University of Basel.

NORTH AND WEST COAST AND INTERIOR OF BRITISH NORTH BORNEO

1. **W. Hotz:** Islands of Banggi, Balambangan and Manawali. 21.V.1914. With a geological map 1:126,720 (from which Enclosure III has been compiled), 6 geological cross-sections, 1:126,720 and a geological sketch-map, 1:20,000 across the central part of Banggi Island.
2. — — Bengkoka Peninsula. 9.III.1915. With a geological map and 4 cross-sections, 1:50,000.
3. — — Paitan Bay (east coast of Bengkoka Peninsula). 5.X.1914. With a geological map, 1:100,000, and a structural sketch-map of Bengkoka Peninsula, 1:300,000.
4. — — East Coast of Marudu Bay. 7.IX.1914. With a geological map, 1:50,000, 2 cross-sections, 1:100,000, and one cross-section, 1:50,000.
5. — — Marudu Bay and Upper Sugut River. 26.VII.1914. With a geological map, 1:50,000, and 2 cross-sections, 1:100,000 (Enclosure V has been compiled from the maps of reports 4 and 5).
6. — — West Coast of Marudu Bay. 22.VII. 1914. With a geological map and 2 cross-sections, 1:75,000.
7. — — Tampasuk district. 18.X.1915. With a geological map, 1:36,360 (from which Enclosure VI has partly been compiled).
8. — — Pulau Tiga and Pulau Burong, N. of Klias Peninsula. 4.IV.1915. With a geological map, 1:15,000, and 2 cross-sections.
9. **W. Hotz:** Northern part of Klias Peninsula. 17.V.1915. With a geological map, 1:20,000, and 2 cross-sections.
10. — — Southern end of Klias Peninsula. 12.VII.1915. With a geological map, 1:20,000, and 3 cross-sections.
11. — — Schlussrapport über die Resultate ölgeologischer Untersuchungen in British North Borneo. 1.XII.1915. Enclosures: Geological map of B.N.B., 1:300,000; Geological map of Klias Peninsula, 1:100,000; Geological sections, 1:300,000; Well-logs, 1:1,000 (of wells 1–4 Klias Peninsula and wells 1–2 Mangalum Island, N. of Klias Peninsula).
12. **G. Niethammer:** Kudat Peninsula-Sequati. 12.VI. 1913. With a geological map, 1:40,000 (from which Enclosure IV has partly been compiled), 8 cross-sections, 1:40,000, and a geological sketch-map of Sequati region, 1:10,000.
13. — — Mantanani Islands (W. of Kudat Peninsula). 20.III.1914. With a geological map, 1:10,000.
14. — — Kota Belud-Marudu Bay. 30.VII.1914. With a geological map, 1:30,480, and 5 cross-sections.
15. — — Putatan and Tampasuk River. 30.XI.1913. With a geological map of Gaya Bay, 1:29,680, and a geological map of Menkabong River and Kota Belud, 1:30,480.
16. — — Jesselton-Papar-Tambunan. 22.VI.1915. With a geological sketch-map, 1:63,360.
17. — — Interior of B.N.B. between Tambunan, Tampias and Paranchangan. 12.IV.1915. With a geological sketch-map, 1:63,360 (from which Enclosure VI has partly been compiled).
18. — — Interior of B.N.B. between Keningau, Tambunan and Labau. 10.IV.1915. With a geological sketch-map, 1:63,360.
19. — — Keningau, Pinanga and Penawan river. 6.XI.1914. With a geological sketch-map, 1:63,360.
20. — — Tenom, Keningau, Kimanis Bay. 5.XI.1914. With a geological sketch-map, 1:63,360.
21. — — Railway-line Membakut, Weston. Beaufort and Tenom. 25.III.1914. With a geological sketch-map, 1:63,360.
22. — — Klias Peninsula. 10.V.1911. With a geological map, 1:20,000, and 15 cross-sections, 1:20,000.

EAST COAST OF B.N.B.

23. **H. Jezler:** Sugut and Labuk rivers. 14.VII.1914. With a geological sketch-map, 1:100,000.

24. **H. Jezler and K. Stamm:** Lahad Datu District (Dent Peninsula):
(*a*) Mittel- und Unterlauf Segama. 31.I.1914.
(*b*) S.Diwata, Subahan und Dadong. 24.I.1914.
(*c*) S.Silibukan, Tabanak und Pulau Sakar. 28.I.1914.
With geological map, 1:50,000 (from which Enclosure VIII has partly been compiled).

25. **K. Stamm:** Sandakan Harbour, östlicher Teil, April, 1914. With a geological sketch-map, 1:100,000.

26. **F. Spiegelhalter:** Sandakan Harbour, westlicher Teil. With a geological sketch-map, 1:100,000.

27. — — Simporna Peninsula. 12.I.1914. With a geological sketch-map, 1:100,000.

28. — — S.Silimpopon, zwischen S.Sarudong und S.Kalabakang. 7.X.1913. With a geological map, 1:50,000, and 4 cross-sections.

29. **M. Reinhard:** S.Sarudong-Tambalunan. 15.IV.1913. With a geological map, 1:20,000.

30. — — S.Kalabakang. 25.VII.1913. With a geological map, 1:20,000.

31. — — Blantian River. 30.VIII.1913. With a geological map, 1:50,000 (from which Enclosure X has been drawn).

32. — — Marutai River. 31.XII.1913. With a geological sketch-map, 1:100,000.

33. — — Klumpang River. 31.XII.1913. With a geological sketch-map, 1:100,000.

34. — — General report concerning the geological investigations, Tawau District and Simporna Peninsula. 22.I.1924. With a geological map, 1:100,000, 9 cross-sections and a geological map of the SE. Coast of B.N.B., 1:633,000.

II. Reports made on behalf of the Anglo-Saxon Petroleum Company

These reports are in the files of the Head Offices of the Royal Dutch/Shell Group (London and The Hague).

1. **M. Blumenthal:** Geology of the Island of Sebatik. 15.Aug.1913. Three geol. maps, 1:10,000; 2 cross-sections, 1:10,000; geol. map, 1:5,000; general map, 1:100,000; 2 preliminary geol. and topogr. maps, 1:10,000.

2. **J. Irving:** Report on a general reconnaissance of SW. B.N.B., including observations on the adjoining Lawas District of Sarawak. Dec. 1935.
Map Lawas area, 1:50,000; map Mengalong-Padas area, 1:50,000; map Klias Peninsula and Beaufort-Papar area with key map, 1:100,000; compilation map, 1:250,000.

3. — — The geology of the State of N. Borneo. July, 1941. Geol. map+legend (2 sheets), 1:500,000; sample locality map, 1:500,000.

4. **P. Leicester:** Geological report on the Lahad Datu District. Nov. 1936.
Geol. map, 1:50,000 (2 sheets); geol. profiles, 1:50,000; vert. geol. sections, 1:25,000; map showing types of survey, 1:100,000; general geol. map, 1:500,000; key map, 1:2,000,000.

5. **H. E. Parsons:** Test-pit reconnaissance of Ganduman area. 14.2.1939.
Geol. map, 1:20,000; geol. map, 1:100,000; stratigr. column, 1:5,000; section, 1:20,000.

6. — — Report on Mangalum core-drilling. Sept. 1939. Map showing location of core-holes, 1:10,000; 4 sections: Hor., 1:1,000, Vert. 1:500; 1 section, Vert. 1:1,000.

7. **R. W. Pooley:** Report on the reconnaissance of the Lawas Basin. 18.1.1938.
Geol. map, 1:50,000; diagrammatic sections, 1:50,000.

8. **J. P. Roothaan and E. Wenk:** Report on a geological reconnaissance of the central part of B.N.B. 7.6.1937.
General geol. map (2 sheets), 1:100,000.

9. **W. F. Schneeberger:** Report on the geology of the NE. coast of Br. N. Borneo. 29.1.1937. Geol. map (3 sheets), 1:100,000; 5 geol. maps, 1:50,000; technical cross-section (2 sheets), 1:50,000; stratigr. columns, 1:50,000; legend, 1:100,000; tectonic map, 1:500,000; key map, 1:500,000.

10. **J. Schoo:** Geology of the island Sebatik. 6.3.1925. Well log Sebatik I, 1:1,000.

11. **P. de Schumacher:** Report on contraflush drilling and augering in Ganduman, Dent Peninsula. Dec. 1939.
Geol. map, 1:10,000; auger map, 1:2,500; 7 sections, 1:2,500; 1 section, 1:1,000.

12. **G. C. L. Sung:** Reconnaissance of the Maruap anticline (Dent Peninsula). July, 1938. Geol. dip map, 1:10,000; map of N. and S. sections, 1:10,000.

13. **E. Wenk:** Report on a rapid geological reconnaissance of SE. Br. N. Borneo and on resulting stratigraphical correlations. 6.10.1938.
Geol. compilation map, 1:100,000; key map, 1:2,000,000; map with stratigr. correlations.

14. — — Report on the geological reconnaissance of the Dent Peninsula. 13.10.1938. Geol. map, 1:50,000 (2 sheets); geol. sections, 1:50,000.

15. **E. Wenk:** Report on the geology of the Lower Kinabatangan area. Dec., 1938.
Two geol. maps, 1:100,000.

16. **E. Wenk:** Supplementary report on Sebahat-Ganduman area. 20.7.1939.
Geol. map, 1:25,000; geol. map, 1:10,000; detail map, 1:2,000.

Postscript during printing:

The reader is referred also to the important and voluminous work: R. W. van Bemmelen, *The Geology of Indonesia*, Government Printing Office, The Hague, 1949, published after the delivery of the manuscript of the present volume. The authors regret that they could not make use of the wealth of information contained in this most comprehensive book on the geology of Indonesia and adjacent archipelagoes, nor discuss the views expressed therein.

APPENDIX I

List of Rock Samples deposited at the Museum of Natural History, Basel

collected by W. HOTZ, H. JEZLER, P. LEICESTER, G. NIETHAMMER, M. REINHARD, P. VAN RHEDEN, F. SPIEGELHALTER, K. STAMM and E. WENK

Number preceded by a * = samples with a thin slide.
Number preceded by a † = chemically analysed samples.
Number followed by p = sample from loose boulder.

It was not always possible to ascertain whether the samples collected by Hotz and Niethammer were taken from outcrops or from loose blocks.

Age indications in the letter classification (e.g. Te_5 refer to determinations by I. M. VAN DER VLERK. The foraminiferal fauna of these samples are listed in Appendix II.

Meaning of Malay words and their abbreviations

B. = batu = rock
Besar = big
Bt. = bukit = hill
Giram = rapid in solid rock
Gg. = gunong = mountain
Kg. = kampong = native village
Kechil = small
K. = kuala = mouth of a river
P. = pulau = island
S. = sungei = river, brook
Tg. = tanjong = river bend, cape (on the coast)
Tagai = Dusun word for salt seepage
Wossoi = Dusun word for waterfall.

SAMPLES COLLECTED BY W. HOTZ (H.), 1914–1915

			ISLANDS OFF NORTH COAST OF NORTH BORNEO (cf. Enclosure III)
			South-east coast of P. Banggi and adjacent islands
*H.	1	limestone, brecciated, with elements of Danau Formation, Tf	NE. coast of P. Kobog
*	2	*idem*, Tf	Bt. Timbang Dayang, S. coast of P. Banggi
	3	sericite-quartz-phyllite	reef off W. end of P. Meriangin Besar
*	4	dolerite	N. coast of P. Meriangin Besar
*	5	limestone with *orthophragmina* and *lithothamnium* (Eocene, Rutten, 1915, p. 13, No. 4)	W. coast of P. Banggi, Tg. near S. end
*	6	radiolarian chert	cliff to the W. of locality of sample 5
			East coast of P. Banggi and adjacent islands
*7	*7a	marly limestone, buff with red spots, with radiolaria and scarce foraminifera, Cret.-Tertiary (Reichel)	P. Batawan
*	8	serpentine	P. Malundangan Kechil
	9	sandstone, fine-grained	Tg. Butan, NE. cape of P. Banggi
*	10	radiolarian chert	NE. coast P. Tagayawan, E. of P. Banggi
*	11	chert breccia with quartz veins	ibid.
*	12	spilite, epidotized and silicified	P. Ruby
*	13	spilite, decomposed	,,
	14	sandstone, fine-grained calcareous	,,
*	15	tuffite	S. Pitagas, P. Banggi E. coast
	16	conglomerate	NW. corner of P. Latoan

*H.	17	marble, silicified, with ilmenite	*South-east coast of P. Banggi*
*	18	marble	N. of P. Modom
†*	19	basalt	ibid.
			small tributary of S.Limbuak
*	20	lherzolite	*P. Manawali and adjacent islands*
*	21	serpentine-breccia	P. Tanjong
*	22	calcareous sandstone, Tf	P. Manawali W. coast
*	23	dunite	ibid.
	24	chromite	P. Manawali S. coast
*	25	dunite	ibid.
*	26	bronzitite	P. Manawali SW. coast
	27	sandstone	ibid.
*	28	chlorite-schist	P. Manawali N. coast
	29	radiolarian chert	ibid.
*	30	epidote-hornblende-schist	,,
*	31	radiolarian chert	P. Manawali E. coast
*	32	bronzitite	P. Manawali SE. coast
*	33	*idem*, olivine-bearing	ibid.
*	34	brecciated dunite	P. Mati
*	35	calcareous chert	,,
			,,
*	36	radiolarian chert	*Interior of P. Banggi*
	37	*idem*, brecciated	S.Mampong
	38	pyrolusite	,,
*	39	serpentine	,,
*	40	spilite	,,
*	41	limestone	S.Sabur
*	42	silicified and calcified serpentine	,,
			,,
*	43	spilite	*West coast of P. Banggi*
*	44	*idem*	N. of K. Limbuak
*	45	sandy limestone, Te_5-f_2	ibid.
*	46	spilite	small island S. of K. Limbuak
	47	conglomerate with elements of Danau Formation	ibid.
*	48	leucogabbro-diabase	N. of S.Limbuak
	49	diabase	S.Pankalan
*	50	reddish-brown limestone with radiolaria and foraminifera, Mesoz.-Tert. (Reichel)	S. Kambongi
			,,
*	51	diabase	
	52	chert, re-crystallized as quartz and chalcedony	,,
	53	sandstone	,,
	54	chert with quartz veins	,,
*	55	serpentine	,,
*	56	porphyritic tuff-breccia	N. of K. Limbuak
*	57	amphibolite	ibid.
			,,
*	58	brecciated limestone, Te_4-$_5$	*P. Balambangan*
†*	59	analcite-diabase	South cape
	60	manganese ore sand	ibid.
*	61	diabase	E. coast, Tg. Sempriok
*	62	marly coral limestone (upper Pliocene-Quaternary, Rutten, 1915, p. 13, No. 3)	SW. coast
			NW. coast, Tg. Limpiang
*	63	serpentine	*North coast of P. Banggi*
*	64	*idem*	head-waters of S.Bengkinit
	65	red clay	ibid.
*	66	uralite-diabase	,,
*	67	*idem*	S.Pitangan
*	68	amphibolite	Gg. Sinambong
*	69	serpentine-breccia with calcite cement	E. of K. Sibumbung
	70	chert	P. Bahayan
*	71	brecciated limestone, Te_3-$_5$	head-waters of S.Sibumbung
*	72	diabase, epidotized and calcified	ibid.
*	73	ferruginous slaty marl	W. of K. Bitara
			K. Bitara

†*H.	74	white, aphanitic rock, resembling massive magnesite, of indeterminable mineral composition‡)	**MARUDU BAY AND BENGKOKA PENINSULA**
*	75	brown limestone with radiolaria and foraminifera, Mesoz.-Tertiary (Reichel)	*South-east coast of Marudu Bay* (cf. Enclosure V) N. of K. Marisimsing
*	76	spilite	head-waters of S.Balayayong, old manganese mine
*	77	diabase-tuff	" Taritipan "
†*	78	diabase	ibid.
	79	chlorite-epidote rock	,,
*	80	amygdaloidal diabase	,,
	81	red shale	,,
	82	manganiferous chert	,,
	83	*idem*	,,
	84	*idem*	,,
	85	manganese ore (psilomelane) with inesite	,,
	86	schistose limestone	S. of manganese mine
			Region south of Marudu Bay
*	87	calcareous sandstone with foraminifera (Neogene, Rutten, 1925a, p. 424)	head-waters of S.Bongon
*	88	spilitic tuff-breccia, epidotized, with clots of prehnite	head-waters of S.Sarimsing
*	89	manganiferous chert	head-waters of S.Sarimsing
	90	argillaceous laminated sandstone	ibid.
	91	psilomelane	,,
*	92	dunite, diallage- and bronzite-bearing	,,
*	93	porphyritic tuff, calcareous	head-waters of S.Kinorom
	94	quartzitic sandstone	upper S.Sarimsing
	95	quartz-sandstone	K. Lowaki, upper S.Kapoakan, head-waters of S.Sugut
	96	calcareous sandstone	upper S.Kapoakan
*	97	porphyritic hornblende-biotite-microgranodiorite	ibid, from salt-water spring
	98	quartz-sandstone	S.Toaran, above Kg. Pampang
	99	*idem*	,, near Kg. Mandanao
*	100	adinole-schist	,, below Kg. Mandanao
*	101	diabase, calcified	ibid.
	102	radiolarian chert	Gg. Rogadin on S.Toaran
*	103	spilite	ibid.
			Bengkoka Peninsula
	104	lignite with sandy streaks	W. coast, Tg. Perawan
	105	limestone with shells	,, Tg. Mafsie
*	106	limestone with foraminifera (Eocene? Rutten, 1925a, p. 423)	,, Kg. Melobang
			South-east coast of Marudu Bay (cf. Enclosure V)
*	107	limestone, brecciated, with foraminifera (old Neogene, Rutten, 1925a, p. 423)	S.Maniupaniu
*	108	limestone with *globigerina*, *lithothamnium* and fragments of *orthophragmina* (Eocene, Rutten, 1925a, p. 423)	S.Marisimsing
	109	marly limestone	S.Salimpodon
*	110	spilite	,,
*	111	spilite	,,
*	112	spilitic breccia with pyrite and blende	old copper mine Pingang-Pingang
			Bengkoka Peninsula
*	113	basalt	E. coast, Telok Gapas
*	114	basalt	,, Tg. Batu, K. Karangan
	114a	lignite	N. coast
	114b	quartz-sandstone	,,
			KLIAS PENINSULA, W. COAST, B.N.B.
*	115	brecciated limestone with foraminifera, Te_{1-3}	" new " island, off W. coast Klias Peninsula

‡An X-ray powder photograph yielded lines which could not be identified with any known mineral. An incomplete chemical analysis gave the result: SiO_2 = 38·7% (by difference); Al_2O_3 = 12·1%; $FeO+Fe_2O_3$ = 5·5%. MgO = 7·1%; Na_2O+K_2O = 0·5%. Loss on ignition = 5·7%.

*H.	116	ankerite from test pit	S. end of Klias Peninsula, near K. Menumbuk
*	117	limestone with *Miogypsina* and small *Lepidocyclina* (Miocene, Rutten, 1921, p. 1143)	P. Burong S. of Labuan
			GUNONG KINABALU (cf. Enclosure VI)
*	118	quartzitic sandstone	S.Sorob, near Kg. Rundai
*	119	calcareous sandstone	S.Kina Taki. W. slope of Kinabalu
	120	slate	S.Tohobang ,, ,,
*	121	indurated argillaceous quartzitic sandstone	,,
*	122	quartzitic sandstone	,,
†*	123	trachytic spilite	head-waters S.Kadamayan, SW. slope of G. Kinabalu
*	124	metamorphic spilite	loose boulder, ibid.
*	125	slate	ibid.
*	126	indurated clay slate	Lobang Lobang cave, SW. slope Kinabalu
	127	slate	ibid.
	128	slate	N. of Kamboranga S. slope Kinabalu
	129	sandstone	ibid.
*	130	argillaceous quartzitic sandstone	,,
*	131	harzburgite, olivine-rich	,,
*	132	dunite, actinolite-rich	,,
*	133	biotite-hornblende-granodiorite	S. of Paka cave, S. spur of Kinabalu
*	134	dunite	ibid.
	135	aplite dike in biotite-hornblende-quartz-monzonite	summit of Gg. Kinabalu
*	136	*idem*	ibid.
*	137	biotite-hornblende-quartz-monzonite	,,
	138	magnetite	,,
	139	no sample	
			P. BURONG AND P. TIGA, north of Klias Peninsula (cf. cross-section Fig. 20)
*	140	diabase	P. Burong
*	141	diabase	ibid.
*	142	red and white, partly silicified limestone, with *Globorotalia* and *globigerina*, Paleocene (Reichel)	,,
*	143	*idem*	,,
*	144	*idem*	,,
*	145	basalt	,,
	146	no sample	
*	147	silicified limestone with *Globorotalia* and *globigerina*, Paleocene (Reichel)	,,
	148	sandstone, from test pit	*P. Tiga*, E. coast
	149	clay	ibid. ,,
	150	clay with fragments of sandstone	,, ,,

SAMPLES OF FORAMINIFERAL ROCKS FROM HOTZ COLLECTION, DETERMINED BY L. RUTTEN

The determinations have not been revised. The indications of the age in the letter classification are based on the species of foraminifera as determined by RUTTEN

			Islands off north coast of North Borneo (cf. Enclosure III)
*H.	151	marl (Miocene, Rutten, 1915, p. 12, No. 1a) = Tf	S. end of P. Balambangan
*	152	limestone (Miocene, Rutten, 1915, p. 12, No. 1b) = Tf	ibid.
*	153	brecciated crystalline limestone with foraminifera and *lithothamnium* (Miocene, Rutten, 1915, p. 12, No. 2) = Tf	,,
*	154	coral limestone (upper Pliocene-Quaternary, Rutten, 1915, p. 13, No. 3)	NW. coast, Tg. Limpiang
*	155	limestone (Eocene, Rutten, 1915, p. 17, No. 5) = Te (+b?)	NE. cape of P. Kobog

*H.	156	limestone (Eocene, Rutten, 1915, p. 14, No. 6) = Ta-b	P. Ruby, E. of P. Banggi
*	157	limestone (Miocene, Rutten, 1915, p. 15, No. 7) = Te	W. coast of P. Banggi, S.Kabongi
*	158	limestone (Oligo-Miocene, Rutten, 1915, p. 16, No. 8) = Te_{2-5}	interior of P. Banggi, S.Mampong
*	159	brecciated limestone (Oligo-Miocene, Rutten, 1915, p. 16, No. 9)	E. coast of P. Banggi
*	160	conglomeratic limestone with small pebbles of quartz and chert (Oligo-Miocene, Rutten, 1915, p. 15, No. 10) = Te	W. coast of Banggi, N. of S.Limbuak
*	161	limestone (Eocene, Rutten, 1915, p. 14, No. 11) = Ta-b	W. coast of P. Banggi, S. of K. Limbuak
*	162	limestone (Eocene, Rutten, 1915, p. 14, No. 12) = Ta-b	S. coast of P. Banggi, S.Mamang
*	163	limestone (Oligo-Miocene? Rutten, 1915, p. 17, No. 14) = Te	W. coast of P. Kobog
			Klias and Bengkoka peninsulas
*	164	oolitic limestone (Tertiary, Rutten, 1921, p. 1144)	reef N. of P. Kalumpunian, N. of Klias Peninsula
*	164a	chert with decomposed ophiolite	ibid.
*	165	limestone (Eocene? Rutten, 1925a, p. 423)	N. of Kg. Melobang, NW. coast of Bengkoka Peninsula

SAMPLES COLLECTED BY G. NIETHAMMER (Nh.), 1911–1914

			KUDAT PENINSULA, northern part (cf. Enclosure IV)
			West coast
*Nh.	1	sandstone, calcareous, foraminiferal (Rutten, 1925a, p. 417), Te_{2-5}	P. Kelambu
	2	conglomerate, fine-grained	Bukit Loro
	3	sandstone, fine-grained, light grey-green	Tg. between P. Kelambu and Tg. Loro
*	4	sandstone, foraminiferal (Rutten, 1925a, p. 417) Te	Tg. Loro
*	5	agglomerate, foraminiferal (Rutten, 1925a, p. 417) Te_2	Tg. Loro
	6	sandstone, brown, argillaceous	hill SW. of Kg. Tomagong (S. Loro)
	7	sandstone, foraminiferal	path SSW of Kg. Tomagong
*	8	sandstone, calcareous	Kuala Loro
*	9	spilite	creek E. of Tg. Bangau
*	10	basalt	ibid.
*	11	dunite-serpentine, calcified	,,
†*	12	diabase	E. of Tg. Bangau
*	13	vein of chalcedony	ibid.
*	14	spilite	Tg. Bangau
	15	spilite	,,
*	16	serpentine	,,
*	17	spilite	,,
	18	spilite	,,
	19p	granodiorite	,,
	20	spilite	,,
*	21	vein of natrolite	,,
	22	vein of quartz	,,
*	23	radiolarian chert	,,
*	24	spilite, zeolitized	,,
*	25	basalt	,,
*	26	spilite	Kuala Bangau
	27	basalt	ibid.
*	28	radiolarian chert with vein of chalcedony	,,
*	29	limestone, marly, red	,,
*	30	radiolarian chert	,,
	31	radiolarian chert	,,
*	32	limestone, marly, brown	,,

*Nh.	33	diabase	path E. of Kuala Bangau
*	34	limestone, foraminiferal (Rutten, 1925a, p. 418), Te_4	ibid.
*	35	limestone, fine-conglomeratic foraminiferal (Rutten, 1925a, p. 418), $Te_{2-5}(+b)$	,,
	36	sandstone, lignitic	S. of S.Kurima, Sequati
*	37	sandstone with pyrite and marcasite	ibid.
	38	sandstone with fossil resin	river 2 km. NE. of Kg. Sequati
	39p	dunite-serpentine	beach NW. of S.Tambaluran
			East coast
	40	limestone, foraminiferal (Rutten, 1925a, p. 417), Ta-b	path from Labuan S.Crotang to Tomagong
*	41	sandstone, conglomeratic with shell-fragments	Kg. Tajau
	42	sandstone, lignitic	Tg. Agung Agung
	43	lignite	ibid.
*	44	amphibolite, banded	Tg. Pengaraban
*	45	plagioclase-amphibolite	ibid.
*	46	diabase-porphyrite	4 km. NW. Kudat
*	47	spilite-breccia	ibid.
	48	spilite	,,
*	49	limestone, brecciated, foraminiferal (Rutten, 1925a, p. 422), $Te_5(+b)$	Kudat, Estate Broese
*	50	sandstone, calcareous	S.Bumbum, near Kuala Bumbum
*	51	limestone, brecciated, foraminiferal (Rutten, 1925a, p. 420, 421) $Te_4(+b)$	ibid., road Kudat-Sequati
*	52	limestone with *globigerina*	,,
	53	sandstone with plant remains	upper S.Bumbum
*	54	serpentine	ibid.
	55	chert breccia	,,
*	56	limestone, sandy, foraminiferal (Rutten, 1925a, p. 421), Te	,,
	57	serpentine	watershed S.Bumbum-S.Loro
*	58	dunite-serpentine	ibid.
	59	serpentine	,,
*	60	limestone, fine conglomeratic, foraminiferal Rutten, 1925a, p. 420) $Te_{2-5}(+b)$	S.Dualog
*	61	limestone, sandy, foraminiferal, Te_4-f_2	E. of Kg. Dualog
			Kudat Bay
*	62	prasinitic breccia (schalstein)	S. of P. Langsana; west coast
*	63	adinole-slate	ibid.
*	64	sandstone, fine-grained, light grey with ripple marks	,,
	65	chert	Pangalan Bay
	66	chert, brecciated	ibid.
*	67	spilitic tuff	,,
*	68	diabase tuff (schalstein)	,,
*	69	spilite-breccia	,,
*	70	diabase	,,
*	71	serpentine, silicified and carbonatized	Tg. E. of Pangalan Bay; south coast
	72	limestone, sandy, fine-conglomeratic (Rutten, 1925a, p. 122; old Neogene)	ibid.
*	73	hydrothermal quartz-calcite rock	,,
*	74	phyllite, calcareous	SW. of Batu Puteh
*	75	spilite	south coast near Batu Puteh
*	76	radiolarian chert	Batu Puteh
*	77	sandstone, fine-grained	SE. of Batu Puteh
*	78	chert with calcite	ibid.
*	79	ophicalcite	,,
*	80	spilite	,,
*	81	chert with calcite	,,
*	82	spilite	,,
	83	spilite	E. of Batu Puteh
*	84	chert	ibid.
*	85	leuco-quartz-diorite	,,
*	86	ophicalcite	,,

*Nh.	87	spilitic tuff breccia (schalstein)	E. of Batu Puteh
*	88	adinole, slaty	ibid.
*	89	schalstein	,,
*	90	spilite, silicified and calcified (schalstein)	,,
*	91	leuco-quartz-diorite-porphyry	,,
*	92	spilite-breccia	,,
*	93	adinole-slate	,,
*	94	leuco-quartz-diorite	,,
†*	95	quartz-diorite	south coast of Kudat Bay, SSW. of Kudat
	96	chert	ibid.
*	97	spilite	,,
*	98	adinole-slate	,,
†*	99	leuco-quartz-diorite	,, SSE. of Kudat
*	100	serpentine, silicified and calcified	,, ,, ,,
*	101	spilite	Tg. Tambarassuk
*	102	ophicalcite	,, ,, Kg. Baru
*	103	spilite tuff, brecciated	Kg. Baru
			Southern part of Kudat Peninsula
			West coast
	104	sandstone, fine-grained, white	Tg. Ayer Manau
†*	105	hornblende-labradorite-andesite, augite-bearing	Tg. Sirar, western part
*	106	augite-hornblende-labradorite-andesite, carbonate-bearing	,, eastern part
*	107	*idem*	Tanjong E. of Tg. Sirar
*	108	*idem*	ibid.
	109	quartzite, inclusion in andesite	Tg. Sirar
*	110	quartz-sandstone, carbonate-bearing, slightly metamorphic	,,
	111	*idem*	,,
	112	*idem*	,,
	113	hornblende aggregation in andesite	,,
	114	sandstone with lens of coal, near andesite	,,
*	115	sandstone with *operculina*, indurated at the andesite contact, ore-bearing (Rutten, 1925a, p. 418)	,,
*	116	sandstone, calcareous	,,
	117p	serpentine	,,
*	118	augite-hornblende-andesite	P. Sirar
*	119	*idem*, with tuff bed	,,
*	120	*idem*, with thin beds and lenses of crystal-tuff	,,
	121	*idem*	,,
*	122	granodiorite-mangerite, inclusion in andesite	,,
*	123	*idem*	,,
*	124	hornblende-andesite, pebble of volcanic agglomerate	,,
*	125	hornblende-augite-andesite, pebble of volcanic agglomerate	,,
	126	hornblende crystals from andesite	,,
	127	hornblende crystals from volcanic agglomerate	,,
*	128	quartz-sandstone, brownish-red	Tg. Taburan Besar
*	129	ankerite, dense	ibid.
*	130	sandstone, fine conglomeratic, foraminiferal (Rutten, 1925a, p. 418), Tb	Tg. Taburan Tamid
	131	sandstone, coaly	S.Sibundu
	132	shale, red	S.Menturi
	133	sandstone, fine-grained	,,
	134	*idem*	,,
			East coast
*	135	quartz-sandstone	Kg. Nangkak
*	136	limestone, foraminiferal, Te_{2-5}	S. of Kg. Nangkak
	137	chert, inclusion in limestone	ibid.
	138	diabase-tuff	,,
*	139	limestone, conglomeratic, foraminiferal (Rutten 1925a, p. 420), Te_{2-5}	,,

*Nh.	140	limestone, conglomeratic, foraminiferal (Rutten, 1925a, p. 419), Td-f(+b)	S.Bengkongan
*	141	limestone, marly	,,
*	142	limestone, foraminiferal (Rutten, 1925a, p. 419, Eocene)	,,
*	143	limestone, conglomeratic, foraminiferal (Rutten, 1925a, p. 420), Te_{2}-$_{5}$(+b)	S.Mangaris
*	144	spilite-tuff, brecciated	path W. of Langkom
*	145	diabase-tuff	ibid.
	146	shale, sandy-calcareous, flysch-like	,,
*	147	sandstone, calcareous, foraminiferal (Rutten, 1925a, p. 419, Eocene)	,,
	148	conglomerate	S.Mangaris, upper course
	149	limestone, foraminiferal (Rutten, 1925a, p. 419), Te_{2}-$_{5}$(+b)	ibid.
*	150	diabase	,,
	151	sandy clay	watershed Mangaris-Loguk
	152	sandstone, fine-grained	ibid.
*	153	sandstone, calcareous flysch-like	S.Sungei
*	154	limestone, foraminiferal (Rutten, 1925a, p. 419), Ta-b	,,
*	155	diabase	,,
	156	diabase	,,
*	157	tuff-breccia, calcified	,,
	158	sandstone, rich in pyrite	,,
*	159	spilite-breccia	,,
			WEST COAST OF NORTH BORNEO
			S.Pandasan area
*	160	quartz-sandstone, flysch-like	S.Kapor
*	161	albite-olivine-gabbro	SW. of Bukit Landa
*	162	spilosite	ibid.
*	163	spilosite	,,
	164	radiolarian chert	,,
*	165	radiolarian chert	,,
	165a	foraminifera (*Bathysiphon?*)	head-waters of S.Kapor
	166	quartzite with veins of calcite	S.Matanau
*	167	marble, quartz- and chlorite-bearing	,,
*	168	spilite, laminated	,,
*	169	chert	,,
	170	diabase, slaty	,,
	171	shale	,,
	172	sandstone, fine-grained, argillaceous, flysch-like	S.Tambung
*	173	chert, calcite-bearing	S.Loguk
*	174	chert	,,
*	175	quartz-sandstone, fine-grained, grey-green	,,
*	176	diabase-tuff	S.Warung
	177	sandstone, calcareous	,,
*	178	sandstone, flysch-like	S.Loguk
	179	sandstone	,,
*	180	diabase-tuffite, carbonate-bearing	northern branch of S.Loguk
*	181	limestone, fine-spathic	ibid.
*	182	diabase-tuff (schalstein)	,,
*	183	sandstone, calcareous	,,
*	184	diabase-tuffite, calcareous	,,
*	185	limestone, fine-spathic	,,
			Kota Belud Region
	186	radiolarian chert	SW. of Kg. Bengkok
	187	chert, re-crystallized and ore-bearing	ibid.
	188	chert	,,
	189	diabase	,,
	190	quartz-sandstone	,,
*	191	quartz-sandstone	W. of Kg. Bengkok
*	192	nephrite	path Tampasuk-Bengkok
*	193	quartz-sandstone with silicified foraminifera (*Lepidocyclina sumatrensis* det. M. Reichel)	ibid.

*Nh.	194	gabbro	S. of Kg. Tampasuk
*	195	uralite-gabbro-diabase, prehnitized	ibid.
	196	quartz vein in diabase, pyrite-bearing	,,
*	197	spilite	,,
*	198	diabase	Bukit Tampasuk
†*	199	spilite	ibid.
*	200	sandstone, fine-grained	,,
	201	spilosite	,,
*	202	radiolarian chert	,,
	203	radiolarian chert	,,
*	204	sandstone, fine-grained	,,
	204a	manganese ore	,,
*	205	olivine-gabbro-diabase	,,
*	205a	olivine-diabase	,,
*	206	olivine-gabbro-diabase, uralitic	,,
	207	olivine-gabbro	,,
*	208	uralite-diabase	,,
*	209	spilosite	,,
*	210	adinole-slate	,,
	211	clay, sandy	,,
*	212	spilosite	,,
	213	argillaceous sandstone, containing wad	,,
	214	peridotite, altered	,,
	215	radiolarian chert with vein of chalcedony	,,
*	216	radiolarian chert	,,
	217	radiolarian chert	,,
	218	psilomelane	,,
*	219	jasper, rich in Fe and Mn	,,
	220	radiolarian chert	,,
*	221	sandstone, calcareous	,,
*	222	spilosite	,,
*	223	spilite	,,
	224	quartz-sandstone	,,
	225	chert-breccia	N. of Bukit Klawat
	226	chert	ibid.
	227	chert-breccia	,,
*	228	radiolarian chert	,,
*	229	spilite-breccia	,,
*	230	chert	,,
*	231	radiolarian chert, re-crystallized	W. foot of Bukit Klawat
*	232	muscovite-quartzite	NE. slope of Bukit Klawat
	233	shale	S.Sarob
	234	quartz-sandstone	,,
	235	sandy clay, laminated	,,
	236	radiolarian chert	creek S. of S.Sarob
	237	spilite	Bukit Binaton, SE. of Kota Belud
*	238	chert, re-crystallized	ibid.
*	239	spilite, epidotized	Bukit Rindian, SE. of Kota Belud
†*	240	chert-like contact rock between pillows of spilitic pillow-lava	ibid.
*	241	spilite	,,
	242	chert-breccia	,,
	243	pebbles of granite, chert and serpentine	Kota Belud
			Tuaran Region
	244	edible earth, white	Kg. Samba
	245	sandstone	Kg. Tambilit
	246	edible earth, red	Kg. Tuaran
	247	sandstone, argillaceous with plant remains	ibid.
*	248	quartz-sandstone	,,
	249	chert, re-crystallized	,,
*	250	quartz-sandstone, flysch-like	,,
	251	sandstone with coal and clay films	Tuaran Estate
	252	clay, red	S.Kilagon
	253	sandstone with thin clay beds	E. of Kg. Kapa
*	254	quartz-sandstone	ibid.

*Nh.	255	hornblende - biotite - granodiorite - porphyry, altered, carbonate-bearing	E. of Kg. Kapa
	256	quartz-sandstone, fine-grained	ibid.
	257	*idem*	,,
	258	sandstone	S.Melapi
	259	quartz-sandstone, fine-grained	,,
			Bukit Melasgeas
			Mangalum Island
	260	sandstone, calcareous, fossiliferous	east coast
	261	quartz-sandstone	ibid.
	262	sandstone	north coast
	263	sandy clay with shells	test pit I
	264	*idem*	test pit IV
	265	sandstone, calcareous	test pit IX
			Mantanani Islands
	266	limestone	main island
	267	mollusca	ibid.
	268a-b	coral-limestone	,,
	269	mollusca	,,
	270a-d	coral-limestone	P. Burong
	271	limestone with *operculina*	,,
	272	limestone with gastropoda	,,
	273	limestone, foraminiferal	,,
	274	limestone with mollusca	,,
			Jesselton-Weston area
*	275	quartz-sandstone	Jesselton
	276	clay, variegated	,,
	277	quartz crystals	Bukit Padang Estate
	278	quartz-sandstone	Membakut
	279	pebble of silexite	Beaufort
	280	sandstone, fine-grained	,,
			Lower course of S.Padas
	281	sandstone, fine-grained	E. of Beaufort
	282	*idem*	mile 63 on railway
	283	sandy clay	mile 64 on railway
	284	chert pebble in shale	ibid.
	285	conglomerate, fine-grained	Rayoh
	286	sandstone with insolation crust	below Tenom
	287	shale, slaty	ibid.
	288	sandstone, flysch-like	,,
*	289	*idem*	Bukit Bilokat
	290	sandstone with coal lenses	Kg. Lantabuan
	291	clay, fine-sandy	,,
			Lower course of S.Pegalan
	292	sandstone, foraminiferal	S.Tipoh
	293	*idem*	S.Pamilan
*	294	shale, red	S. Mangkalias
*	295	sandstone, calcareous	S.Pampan
	296	sandstone, flysch-like	ibid.
	297	clay, red	S.Siwatan (Kimanis)
			INTERIOR
	298	sandstone	Witti Range
			S.Labau, head-waters of S.Milian
	299	sandy clay	S.Lobo
	300	clay, concretionary	S.Tamanggurai-S.Pingas
	301-5p	sandstone and quartzite pebbles from gravel banks	S.Milian
	306	spilite-breccia, altered	Bt. Mokosogo
	307	diabase-tuffite, altered	,,
*	308	spilite	,,
*	309	spilitic breccia, calcareous	,,
*	310	spilite	,,
	311	clay, red	S.Kasoko
*	312	diabase-tuffite	,,
	313p	quartzite pebble	S.Talipassuk
	314	quartz-sandstone	S.Biemangon

Nh.	315	shale, red	S.Labau
	316	shale, grey	,,
*	317p	diabase, altered	S. Kinayo
*	318p	diabase	,,
*	319p	spilite	,,
*	320p	chert, calcitic	,,
*	321p	spilite, variolitic	,,
	322	sandstone, argillaceous	S.Matualua
	323	shale, red	S.Kinayo
	324	siliceous concretions in shale	,,
*	325	quartzitic sandstone, flysch-like	,,
*	326	limestone, argillaceous ferruginous	,,
*	327	shale with veins and layers of quartz	S. Gentanan
	328	sericite-talc-phyllite	,,
	329	*idem*	,,
	330	sandstone	Gg. Tolot
	331	sericite-phyllite	,,
	332	sandstone	,,
			S.Pegalan, head-waters S.Pegalan
	333	sandy clay	Kuala Bayayo
	334	quartz-sandstone, fine-grained	Kuala Belatikon
	335	clay with lignite lenses	S.Tendulu
			S.Pangas
*	336	limestone, foraminiferal (Rutten, 1925a, p. 424), Ta-b	S. Pangas
*	337	limestone, foraminiferal with calcite veins	,,
*	338	diabase-porphyrite	,,
*	339	spilitic tuff-breccia	,,
*	340	*idem*	,,
			S.Kingaran
	341	slate	lower course of S.Kingaran
*	342	slate	ibid.
	343	slate	,,
	344p	tuff-breccia (spilitic?)	,,
	345p	*idem*	,,
	346p	*idem*	,,
	347p	*idem*, slaty	,,
	348p	slaty, pyrite-bearing	,,
*	349p	limestone, argillaceous ferruginous	,,
	350p	diabase	,,
	351p	limestone	,,
*	352p	limestone, re-crystallized, silicified	,,
*	353p	tuffite, calcareous	,,
*	354p	limestone, foraminiferal (Rutten, 1925a, p. 425, Eocene)	,,
	355	sandstone, foraminiferal	,,
	356	sandstone	upper course of S.Kingaran
	357	slate, sandy	ibid.
	358	*idem*	,,
	359	slate	,,
	360	graywacke	,,
	361	phyllitic slate	,,
			Labuk River, head-waters S.Melaut
	362p	slate	upper course of S.Melaut
*	363	sandstone, calcareous, graphitic	S.Kirokot
*	364	slate	,,
*	365	sericite-phyllite	,,
	366	sandstone	,,
*	367	spilitic tuff-breccia	S.Kutiang
*	368	spilitic tuff-breccia, slaty (schalstein)	,,
*	369	spilite	,,
	370	sandstone, flysch-like	,,
	371	phyllitic slate	S.Baya-Baya
	372	quartz-sandstone, fine-grained	ibid.
*	373	arkose, schistose	,,

	Nh. 374	arkose, schistose	S.Taralamas
*	375	chlorite-crocidolite-schist (schalstein)	,,
	376	slate	,,
	377	slate	*S.Liwagu Kagibangan*
	378	slate	S.Kotop
	379	quartz-sandstone	Bukit Gamut
	380	quartz dyke in Slate Formation	ibid.
	381	phyllitic slate	,,
	382	quartz lens in sandstone	S.Liwagu Kagibangan
	383	diabase	ibid.
	384	slaty argillaceous sandstone	,,
*	385	ophicalcite	,,
*	386	limestone, silicified, with *Lepidocyclina sumatrensis* (det. M. Reichel)	,,
*	387	spilite-breccia, calcified	,,
*	388	*idem*	,,
	389	chert-breccia	,,
	390	slate-breccia, silicified	,,
	391	sericite-quartz-phyllite, conglomeratic	,,
*	392	adinole-slate	,,
	393	adinole (?) with quartz-talc lens	,,
	394p	chert	,,
	395	*idem*	,,
*	396	slate, calcareous	*S.Liwagu Kuananan* (cf. Enclosure VI)
*	397	spilite-tuff, calcareous	upstream Kg. Tampias
*	398	*idem*	ibid.
*	399	sandstone, argillaceous	,,
*	400	spilite-tuffite, carbonate-bearing	,,
*	401	slate	,,
	402	sandstone	path Rendagong-Ranau
*	403	spilite-tuffite, calcareous	upper course of S.Liwagu Kuananan
*	404	*idem*	ibid.
	405	tuffite breccia	,,
*	406	limestone, re-crystallized	,,
	407	porphyritic border facies of hornblende-quartz-monzonite	,,
*	408	*idem*	,,
	409	potash-soda-felspar, Carlsbad-twin, from rock Nh. 407	,,
*	410	porphyritic biotite - hornblende - microquartz - monzonite	,,
†*	411p	hornblende-quartz-monzonite, coarse-grained	,,
*	412	albite-uralite-diabase	,,
*	413	biotite - hornblende - quartz - monzonite, micro-granitic	S.Masilo
*	414	biotite-hornblende-microgranodiorite	,,
*	415	sandstone, fine-conglomeratic	*S.Sugut, head-waters* (cf. Enclosure VI) *S.Merali*
*	416	biotite-hornblende-microgranodiorite	lower course of S.Merali
†*	417	*idem*	Bukit Kargan
*	418	hornblende-biotite-microgranodiorite, altered	ibid.
*	419	biotite-hornblende-microgranodiorite	S. slope of Bukit Kargan
*	420	porphyritic hornblende-biotite-microgranodiorite	Kg. Lansat
*	421	vitrophyric hornblende-biotite-dacite, carbonate-bearing	above Kg. Lansat
†*	422	hornblende-biotite-granodiorite-porphyry, augite- and hypersthene-bearing	ibid.
*	423	biotite-rhyodacite	below Kg. Tadul
†*	424	*idem*	hill between S.Merali and S.Kenanapun
	425	*idem*	below Kuala Bawain
*	426	crumbling clay	ibid.
*	427	gabbro, decomposed	,,
			S.Merali

Nh.	428	clay, marly	S.Merali
*	429	slate, sandy calcareous	,,
*	430	tuffite, calcareous spilitic	,,
*	431	spilitic tuff-breccia	,,
	432	spilite-tuff, schistose	,,
*	433	shale	,,
	434	quartz-sandstone, flysch-like	,,
	435	sandy breccia, flysch-like	,,
	436	sandstone, flysch-like	,,
	437	argillaceous sandstone, flysch-like	,,
			S. Makadau
	438	chlorite-pegmatite	Kg. Tagis
*	439	aplite and pegmatite	,,
*	440	harzburgite-serpentine	Bukit Rinantai
	441	lateritic soil with pisolitic iron ore	,,
	442	pegmatite	,,
	443	pegmatite with hornblende	,,
	444	plagioclase (oligoclase) from pegmatite	,,
*	445	spilite	,, NE. slope
*	446	leucodiabase	,,
*	447	diabase, brecciated	,,
*	448	biotite-hornblende-granodiorite-porphyry, garnet-bearing	below Kuala Nulumat
*	449	serpentine with nephrite	S.Makadau N. of Kg. Nulumat
*	450	augite-hornblende-biotite-microgranodiorite	ibid.
*	451	biotite-augite-microgranodiorite	,,
*	452	hornblende - biotite - augite - microgranodiorite hypersthene-bearing	,,
*	453	zoisite-fels	,,
*	454	serpentine with jadeitite	,,
*	455	serpentine	,,
	456	*idem*	,,
*	457	*idem*	,,
	458	radiolarian chert	,,
	459	*idem*	,,
*	460	jadeitite	,,
*	461	serpentine	,,
*	462	*idem*	,,
*	463	*idem*	,,
	464	phyllite	,,
*	465	slate, fine-sandy	,,
*	466	slate, sandy	,,
*	467	dunite, serpentinized	,,
*	468	hornblende-granodiorite-porphyry, augite-bearing	S.Makadau NW. of Kg. Nulumat
	469	*idem*	ibid.
			Paranchangan
*	470	diopside-biotite-quartz-monzonite-porphyry	between S.Lohan and S.Bangkatan
*	471	augite - biotite - diorite - porphyry, hypersthene- and hornblende-bearing	SW. of Paranchangan
	472	chert-breccia	ibid.
†*	473	hornblende - biotite - quartz - gabbrodiorite - porphyry, hypersthene bearing	,,
			S. Langanan
	474	biotite-rhyodacite, garnet- and hypersthene-bearing	below Kg. Nabung near Paranchangan
	475	quartzite	hill on the right-hand bank of S.Langanan, above Kg. Nabung
*	476	biotite-plagioclase-hornfels, prehnite-bearing	below Kg. Tambulong
	477	hornblende-granodiorite	Kg. Tambulong
*	478	hornblende-biotite-granodiorite	path between Kg. Tambulong and Kg. Nulumat
*	479	biotite-plagioclase-hornfels	Kuala Mamut
*	480	quartzitic sandstone	ibid.
*	481	microgranitic hornblende-biotite-quartz-monzonite	,,

			S.Bangkatan
*Nh.	482	dunite, actinolite-bearing	head-waters of S.Bangkatan
*	483	albite-diabase	path Ranau-Paranchangan, mile III
*	484	albite-uralite-gabbro	ibid.
			S.Lohan
*	485p	epidote-fels	S.Lohan, along path Ranau-Paranchangan
	486p	quartzitic sandstone	ibid.
	487p	chert	S.Nanukan, along path Ranau-Paranchangan
*	488	lherzolite, olivine-rich	Bukit Bagahunan, along path Ranau-Paranchangan
*	489	lherzolite, hornblende-bearing	ibid.
*	489a	lherzolite, garnet-bearing, with diallage-hornblende myrmekite	,,
			S. Kenanapun
	490	biotite-hornblende-rhyodacite	near Kg. Tadul
	491	sandstone, fine-grained	above Kg. Tadul
*	492	diabase	ibid.
			S.Bayan (branch of S.Merali)
*	493	saussurite-uralite-gabbro	S.Bayan
*	494	*idem*	,,
*	495	*idem*	,,
*	496	lherzolite	,,
*	497p	saussurite-gabbro	head-waters of S.Bayan
			KLIAS PENINSULA
	498	conglomerate, fine-grained, Batu Punggul Formation	S. of Kg. Batu Loang
*	499	limestone, foraminiferal (Rutten, 1921, p. 1142), Te_{4-5}	S.Siliko
	500p	conglomerate, fine-grained, polymict, Batu Punggul Formation	,,
501/	502	no samples	
	503	clay	S.Nenungan
	504	sandstone with plant remains	S.Sabong near Mansat
	505	sandstone, argillaceous, concretionary	S.Kalampon near Mansut
	506	sandstone, concretionary	S.Kalampon
	507p	chert	,,
	508	sandstone concretion with pyrite	,,
	509	concretionary shale with pyrite	,,
	510	sandstone	,,
	511	sand	Kapayan, S. of Mansat
	512	pebbles from the base of the Kapayan Formation	ibid.
	513	concretionary shale, Sabong Formation	S.Tungulian
*	514	limestone, fine-grained, brownish-grey with globigerina (det. M. Reichel Cret.? Tert.?)	,,
	515	sandstone, fine-grained, argillaceous	branch of S.Tungulian
	516	sandstone containing pitch	S.Beajik
	517	sandstone	branch of S.Beajik
	518	marly limestone	S.Blanot
	518a	siliceous limestone	,,
	519	limestone with lithothamnium	,,
	520	sandstone, Sabong Formation	,,
	521	*idem*	Siampak, Tg. Aru
	522	limestone concretion, bituminous	S.Napassu
	523	gypsum	?
	524	*idem*	cave near Batu
	525	shell cores	S.Batu Loang

SAMPLES COLLECTED BY J. J. PANNEKOEK VAN RHEDEN (Rh.), 1909–1910

			KLIAS PENINSULA
*Rh.	1	sandstone, calcareous foraminiferal, Te_{2-5}	Tg. Nosong
	2	sandstone	Klias
			KUDAT BAY
*	3	limestone breccia with fragments of pre-Tertiary rocks, foraminiferal, Te_5-f_2(+b)	Estate Broese near Kudat

*Rh.	4	*idem*, $Te_{3-5}(+b)$	Estate Broese near Kudat
*	5	serpentine, calcified	ibid.
*	6	*idem*	,,
	7	limestone, spathic	beach near Kudat
*	8	limestone, brecciated with fragments of pre-Tertiary rocks, foraminiferal, $Te_5(+b)$	ibid.
*	9	hornblende-schist	S. coast of Kudat Harbour, near P. Tigasamil
*	10	chlorite-schist	ibid.
*	11	cataclastic granite with accessory garnet and calcite veins	,,
	12	gabbro	,,
	13	calcareous sandstone	,,
	14	chert	,,
	15	calcareous sandstone, foraminiferal (Rutten, 1925a, p. 422, old Neogene)	,,
*	16	calcareous sandstone, brecciated, foraminiferal, $Te_5(+b)$	,,
	17	quartzitic sandstone	,,
*	18	chlorite-schist	,,
	19	tuff-breccia	,, 500 m. W. of P. Tigasamil
	20	quartzitic sandstone	,, 1 km. W. of P. Tigasamil
	21	tuff-breccia	,,
	22	quartzitic sandstone	S. coast of Kudat Harbour, near P. Tigasamil
	23	tuff	ibid.
	24	tuff, silicified	,, Batu Puteh
*	25	chert-breccia	,, near Batu Puteh
	26	quartzitic sandstone with vein of calcite	,, peninsula S. of P. Langsana
	27	*idem* with quartz vein	,, ,, ,, ,,
	28	calcareous sandstone, foraminiferal (Rutten, 1925a, p. 421, 422, Old Neogene)	Johnstone Bluff, Kudat
	29	sandstone, fine-grained	Kudat
*	30	calcareous sandstone with fragments of ophicalcite, foraminiferal (Rutten, 1925a, p. 422, Old Neogene), $Te_{1-4}(+b)$	near Kudat Residency
			WEST COAST OF KUDAT PENINSULA
	31	recent littoral breccia	between Sequati and Agal Point
	32p	hornblende-granodiorite	between Agal Point and Agal Bay
*	33	olivine-gabbro	Tg. Sampangmangio
			SANDAKAN PENINSULA
*	34	dacitic tuff-breccia with vitrophyric lapilli and fragments of plagioclase and augite, rich in ash	northern part of P. Berhala, E. coast of the island
	35	tuff-breccia	ibid.
	36	*idem*	,,
*	37	calcareous dacitic tuffite-breccia, alternating with fine tuffaceous marl	,,
*	38	strongly calcareous dacitic tuffite-breccia, rich in vitric material, with fragments and idiomorphic crystals of oscillatory andesine/labradorite and corroded quartz	,,
*	39	medium-grained, slightly calcareous vitric tuff with fragments of plagioclase and augite	,,
	40	tuff, fine-grained	,,
*	41	vitric tuff-breccia with few crystals of plagioclase, showing oscillatory zoning	,,
	42	tuff-breccia	,,
*	43	dacitic tuff-breccia rich in vitric material, with idiomorphic crystals of plagioclase and corroded quartz and with fragmental grains of plagioclase, quartz and augite	N. point of P. Berhala
	44	tuff-breccia	ibid.
*	45	slightly calcareous dacitic vitric crystal-tuff, medium-grained	,,
	46	tuff-breccia	,,
	47	calcareous sandy tuffite	cliffs on coast near Sandakan
	48	sandy tuffite	ibid.

	Rh. 49	sandy tuffite with quartz vein	cliffs on coast near Sandakan
	50	calcareous sandy tuffite	ibid.
	51	laminated sandy argillaceous tuffite	Sandakan
	52	sandy tuffite	,,
*	53	calcareous dacitic mixed vitric, lithic and crystal-tuffite, coarse-grained	between Tg. Prapat and Sandakan
*	54	*idem*	Tg. Prapat near Sandakan
	55	sandy calcareous tuffite with veinlet of calcite	ibid.

SAMPLES COLLECTED IN 1913–1914 BY M. REINHARD (R.), F. SPIEGELHALTER (Sp.), H. JEZLER (J.) AND K. STAMM (St.)

The samples are numbered from 1 to 234, irrespective of the collector

SOUTH-EAST COAST. Blantian River and its upper tributaries, Cowie Harbour region (cf. Enclosure X)

*R.	1	red radiolarian chert with white quartz veinlets	S.Blantian
*	2	reddish fine-grained flysch-like calcareous sandstone with veinlets of calcite	,,
*	3	green flysch-like quartzitic sandstone, slightly calcareous	,,
*	4	porphyritic diabase, gray-green, ophitic, with white veinlets of calcite	,,
*	5	spilite, dark-green to brown, compact, brecciated, with slickensides	,,
*	6	chlorite-pumpellyite rock, light to dark-green and brown, serpentine-like, with veinlets of calcite and zeolites	,,
†*	7	spilite, light green, microlitic, slightly brecciated, with amygdules and veinlets of calcite	,,
*	8	serpentine-chlorite schist, green with rusty slickensides	,,
*	9	fine-grained greenish-grey brecciated sandstone	,,
*	10	albite-gabbro, medium-grained, slightly foliated, brecciated, with slickensides coated with chlorite	,,
*	11	serpentine, light and dark green, with a dense network of slickensides	,,
*	12	fine-grained, greenish-grey, slightly calcareous sandstone, brecciated, with slickensides	,,
*	13	spilite, aphanitic, spotted green and brownish, brecciated, with slickensides and calcite veinlets	,,
	14	siliceous shale, squeezed and brecciated	,,
	15	fine-grained, grey flysch-like sandstone with thin layers of shale	,,
	16p	coarse-columnar actinolite-schist	,,
*	17p	compact amygdaloidal spilite, calcite in the amygdules and in veinlets	,,
*	18p	ophicalcite	,,
	19p	pegmatite	,,
*	20p	fine-grained flysch-like calcareous sandstone	,,
*	21p	dark-green aphanitic brecciated spilite with small amygdules filled with calcite	,,
†*	22p	banded olivine-gabbro, medium-grained	,,
*	23p	troctolite, medium-grained, streaky	,,
†*	24p	olivine-gabbro, medium-grained	,,
*	25p	olivine-rich lherzolite, brecciated	,,
†*	26p	light-green compact brecciated spilite, calcite in small amygdules and in veinlets	,,
*	27p	troctolite, medium- to coarse-grained, streaky, plagioclase completely altered to saussurite, olivine serpentinized	,,

*R.	28	uralite-diabase, microlitic, brecciated, with pumpellyite in veinlets	S.Blantian
*	29	uralite-diabase	,,
	30	fine-grained sandstone, brecciated	,,
*	31	fine-grained red sandstone	,,
*	32	spilite with slickensides	,,
*	33	saussurite-amphibolite	top of Gg. Tambuku
	34p	serpentine	S. Paninsau
*	35	harzburgite-serpentine, with saussurite	,,
*	36p	leucogabbro, saussuritized	S.Blantian
*	37p	harzburgitic talc-schist	,,
†*	38p	troctolite, medium-grained, streaky	,,
*	39p	spilite, numerous small amygdules filled with calcite	,,
*	40p	serpentine	,,
*	41p	leucogabbro, medium-grained, streaky, with nodules of ± serpentinized olivine	,,
*	42p	ophicalcite	,,
*	43p	olivine-gabbro, medium-grained	,,
†*	44	plagioclase-bearing serpentinized dunite, plagioclase completely saussuritized	S.Paninsau
*	45p	hornblende-chlorite-albite-gneiss	,,
*	46p	ophicalcite	,,
*	47p	troctolite, serpentinized and saussuritized	,,
*	48p	ophicalcite	,,
*	49p	ophicalcite	,,
*	50p	spilite, brecciated, with slickensides	,,
*	51p	brecciated albite-chlorite-epidote-schist (schalstein)	,,
*	52p	saussurite-uralite-gabbro, streaky, slightly brecciated	S.Blantian
*	53p	olivine-gabbro, cataclastic	,,
*	54p	troctolite, medium-grained	,,
*	55p	*idem*	,,
*	56p	*idem*, cataclastic	,,
*	57p	*idem*, cataclastic, streaky	,,
*	58p	uralite-gabbro	,,
*	59p	*idem*	,,
*	60p	olivine-gabbro, cataclastic	,,
*	61p	uralite-gabbro	,,
*	62p	olivine-rich troctolite, plagioclase completely saussuritized	,,
*	63p	olivine-gabbro	,,
*	64p	ophicalcite	,,
*	65p	pebble of quartz with siderite	,,
	66p	*idem*	S.Masmas
	67p	quartz pebble	,,
			Simporna Peninsula
†*	68	vitrophyric hornblende - bytownite - andesite, hypersthene-bearing, with flow structure	P. Klumpang
*	69	vitrophyric hornblende-bytownite-andesite, augite-bearing, with flow structure	,,
*	70	*idem*	,,
*	71	*idem*	,,
*	72	*idem*	,,
*	73	pilotaxitic hypersthene-augite-labradorite-andesite	,,
*	74	coarse-grained foraminiferal sandy-calcareous crystal-lithic tuffite	S.Klumpang
*	74a	*idem*	,,
*	75	medium-grained fossiliferous crystal-lithic tuffite	,,
*	76	tuffaceous clay, light green, carbonate-bearing	,,
*	77	dacitic crystal-lithic tuffite, carbonate-bearing	,,
*	78	fine to medium-grained calcareous crystal tuffite, well stratified	,,

*R.	79	medium-grained fossiliferous crystal-tuffite	S.Klumpang
*	80	sub-doleritic hypersthene-basalt with relics of olivine and microlites of pigeonite-augite	,,
†*	81	sub-doleritic hypersthene-basalt with microlites of pigeonite-augite	,,
	82*	*idem*, vesicular	,,
	83p	quartz pebble	,,
*	84	diabase-tuffite, dark green, splintery (adinole-slate)	,,
			INTERIOR. Middle Kinabatangan-Milian River (cf. Enclosure VII)
*	85	spilite, grey-green	Kuala Tongod (left-hand tributary)
*	86	diabase-tuff, dark green	ibid.
*	87	spilite, slightly porphyritic, dark greenish-grey	,,
*	88	harzburgitic serpentine	Kuala Pangak (small left-hand tributary from Bt. Tingka, between S. Karamuak and S.Sinoa)
*	89	porphyritic diabase	,, ,, ,, ,,
*	90	olivine-rich lherzolite with hornblende and spinel	,, ,, ,, ,,
*	91	uralite-gabbro, medium-grained	,, ,, ,, ,,
*	92	rhyodacite with phenocrysts of quartz, potash-soda-feldspar and biotite	,, ,, ,, ,,
*	93	lherzolite, olivine-rich	,, ,, ,, ,,
*	94	troctolite	,, ,, ,, ,,
*	95	porphyritic diabase	,, ,, ,, ,,
			SOUTH-EAST COAST. Cowie Harbour region
*Sp.	96	porphyritic hornblende - hypersthene - micro - quartz-diorite	hill W. of Tawau
*	97	*idem*	ibid.
*	98	fluidal hyalopilitic hypersthene-bearing labradorite-andesite with relics of resorbed hornblende and biotite	Batu Tinagat E. of Tawau
*	99	Hyalopilitic hypersthene-bearing biotite-labradorite-andesite with relics of hornblende, rich in haematite	,, ,,
*	100	fluidal hyalopilitic hypersthene-labradorite-andesite with relics of hornblende and microlites of pigeonite-augite	,, ,,
*	101	*idem*	,, ,,
*	102	*idem*	,, ,,
*	103	fluidal hyalopilitic hypersthene-labradorite-dacite with relics of hornblende and biotite and microlites of pigeonite-augite	,, ,,
*	104	fluidal hyalopilitic hypersthene-labradorite-andesite with relics of hornblende and biotite and microlites of pigeonite-augite	,, ,, ,, ,,
*	105	Hyalopilitic augite-bearing hypersthene-labradorite-andesite with relics of hornblende and microlites of pigeonite-augite	,, ,,
*	106	fluidal hyalopilitic hypersthene-biotite-labradorite-andesite, biotite largely resorbed, with microlites of pigeonite-augite	,, ,,
*	107	fluidal hyalopilitic hypersthene-dacite with relics of a mafic (biotite or hornblende)	S.Tawau
	108	tuffaceous sandy clay	,,
*	109	hyalopilitic biotite-hornblende-dacite	,,
*	110	*idem*	,,
*	111p	hyalopilitic augite - hypersthene - labradorite - dacite with relics of hornblende and biotite and microlites of pigeonite-augite	,,
*	112	hyalopilitic hornblende-hypersthene-labradorite-dacite with relics of biotite and microlites of pigeonite-augite	,, ,,
*	113p	hyalopilitic hypersthene-bearing biotite-hornblende-labradorite-dacite	,,

*Sp.	114	Hyalopilitic hypersthene-labradorite-dacite with relics of biotite and hornblende	S. Tawau
*	115p	pilotaxitic augite-labradorite-dacite with ground-mass rich in pigeonite-augite	,,
*	116	vitrophyric hornblende-hypersthene-labradorite-dacite with relics of biotite	,,
*	117p	hyalopilitic hornblende-biotite-dacite	,,
*	118p	hyalopilitic biotite-hornblende-dacite, rich in glass and haematite	,,
*	119	hyalopilitic hypersthene-augite-bytownite-andesite with calcareous inclusions and calcite in cavities of ground-mass and microlites of pigeonite-augite	,,
†*	120	hyalopilitic hypersthene-bearing olivine-augite-basalt with microlites of pigeonite-augite	,,
			North-east coast of Simporna Peninsula and P. Timbun Mata
*	121	vesicular hyalopilitic hypersthene-augite-labradorite-andesite	Mt. Wyatt, 15 km. SE. of Kuala Tingkayu
†*	122	hyalopilitic augite-hypersthene-bytownite-andesite with microlites of pigeonite-augite	20 km. W. of Simporna
*	123	hypersthene- and biotite-bearing hornblende-quartz-diorite-porphyry	E. cape of Timbun Mata
†*	124	amygdaloidal perlitic hyalopilitic augite-bearing hypersthene-andesite	5 km. SSW. of Simporna
	125	brecciated red and yellow spotted quartzite	S. coast of P. Timbun Mata
*	126	harzburgitic serpentine	coast NW. of Simporna
*	127	fine-grained brownish-red calcareous sandstone	ibid.
*	128	brecciated uralite-diabase with zeolites in veinlets	Mt. Wyatt, 15 km. SE. of Kuala Tingkayu
			EAST COAST. Dent Peninsula
*J.	129	Hyalopilitic hypersthene-bearing hornblende-augite-labradorite-andesite, hornblende resorbed, ground-mass rich in pigeonite-augite	watershed S.Sebahat-S.Maruap
*	130p	hyalopilitic augite-labradorite-andesite with microlites of pigeonite-augite and resorbed hornblende, brecciated	S.Silibukan
*	131	hyalopilitic augite-labradorite-andesite with microlites of pigeonite-augite, biotite-, hornblende- and hypersthene-bearing	,,
*	132	carbonate-bearing andesitic conglomerate-agglomerate with components of hyalopilitic augite-labradorite-andesite	,,
*	133	andesitic tuffite-breccia with lapilli of vitrophyric and hyalopilitic hornblende- and more abundant augite-labradorite-andesite	,,
*	134	streaky dacitic-andesitic agglomerate with components of biotite- and hypersthene-bearing hornblende-labradorite-dacite and andesite	,,
*	135	weathered hyalopilitic biotite-bearing hornblende - labradorite - andesite with pyroxene microlites	,,
*	136	hyalopilitic biotite - hornblende - hypersthene - augite-labradorite-andesite with pigeonite-augite in ground-mass, mafics variously resorbed	,,
			Segama river system
*St.	137	calcareous andesitic crystal-tuffite	S.Segama, lower course, from Kuala Telewas downstream
*J.	138	conglomerate with small pebbles of spilite, diabase, hornblende-gneiss and quartzite	ibid., Bedakson Hill
*	139	fine-grained tuffaceous argillaceous sandstone	Lower Segama
	140	tuffaceous loam	ibid.
	141	tuffaceous spilitic breccia, foliated	,,
	142	*idem*	,,
			S.Segama, lower course, from Kuala Telewas downstream

J.	143	tuffaceous spilitic breccia, foliated	S.Segama, lower course, from Kuala Telewas downstream
*	145	saussuritic and uralitic flaser-gabbro	ibid.
	146	spilite with numerous minute calcite-filled amygdules	,,
	147	breccia of crystalline schists	,,
*	148	actinolite-muscovite-schist, garnet- and clino-zoisite-bearing	,,
	149	decomposed amygdaloidal spilite	,,
*	150	amygdaloidal spilite, minute amygdules filled with delessite, albite and zeolite	S.Batu Tatak, right-hand tributary of Lower Segama
	151	white radiolarian chert	ibid.
	152	brecciated decomposed peridotite	,,
*	153	medium-grained calcareous crystal-tuffite	,,
†*	154	hyalo-pantellerite; rare albite phenocrysts in a glassy ground-mass	,,
*	155	spilite with zeolite-filled veinlets	,,
	156	green crumbling clay	,,
	157	white tuffaceous clay	S.Tabin, right-hand tributary of Lower Segama
*	158	calcite-chlorite-schist = adinole slate	ibid.
	159	ophiclacite	,,
	160	fine-grained argillaceous sandstone	,,
	161	white tuffaceous clay	,,
	162	fossiliferous limestone	,,
	163	radiolarian chert	,,
*	164	brecciated gabbro	,,
	165	white tuffaceous clay	,,
*	166	andesitic crystal tuffite	,,
*St.	167	dioritic hornblende-gneiss	S.Telewas, right-hand tributary of Segama (cf. Enclosure VIII)
	168	calcareous andesitic tuffite-breccia	S.Telewas, right-hand tributary of Segama. S. Segama, middle course, from Kuala Telewas upstream (cf. Enclosure VIII)
*	169	medium-grained diorite, decomposed	ibid.
*	170	andesitic tuffite-breccia, rich in vitric material and plagioclase	,,
*	171	spilitic tuff	,,
*	172	andesitic tuffite-breccia, rich in pyroxene and plagioclase crystals and in vitric material	,,
*	173	chlorite-epidote-schist	,,
*	174	albite-chlorite-schist, epidote-bearing	,,
*	175	chlorite-schist, epidote-bearing	,,
*	176	plagioclase-hornblende-epidote-gneiss, pyrite-bearing	,,
*	177	plagioclase-epidote-hornblende-gneiss	,,
*	178	epidote-hornblende-schist with streaks of plagio-clase	,,
*	179	hornblende-plagioclase-hornfels-gneiss	,,
*	180	hornblende-plagioclase-gneiss	,,
*	181	diorite, slightly gneissic	,,
*	182	mela-diorite, streaky	,,
*	183	diabase	,,
*	184	diabase with slickensides	,,
	185	amygdaloidal spilite	,,
*	186	hornblende-plagioclase-hornfels-gneiss	,,
	187	dioritic rock, brecciated and decomposed	,,
*	188	spilite-breccia	,,
†*	189	keratophyre (= aegirine soda-trachyte)	,,
*	190	spilite with accessory biotite and few small amygdules	,,
*	191	*idem*	,,
*	192	conglomeratic uralite-diabase-tuff	,,
	193	schistose serpentine	,,
*	194	uralite-saussurite-gabbro	,,
*	195	radiolaria-bearing black limestone	,,

*St.	196	ophicalcite	S.Segama, middle course, from Kuala Telewas
	197	conglomerate with ophiolitic elements and calcite cement	upstream
*	198	amygdaloidal spilite	,, ,,
*	199	*idem*, in contact with red limestone	,, ,,
	200	white tuffaceous clay	,, ,,
			Darvel Bay and surrounding area
*J.	201	spilite-breccia with veinlets of calcite	S.Subahan (cf. Enclosure IX)
†*	202	uralite-gabbro-diorite	,,
*	203	spilite-breccia with veinlets of calcite and zeolite (schalstein)	,,
*	204	fine-grained sandstone with veinlets of calcite and slickensides	,,
*	205	fine-grained tuffaceous sandstone	,,
*	206	coarse-grained calcareous andesitic mixed vitric-lithic-crystal-tuffite with foraminifera	,,
*	207	quartzite	,,
*	208	saussuritite, greenish-white, compact, slightly brecciated	,,
*	209	red and yellow brecciated radiolarian chert	,,
*	210	spilite with few small amygdules, brecciated	,,
*	211	uralite-diabase, brecciated	S.Silibukan-Matamba, Dent Peninsula
	212	schistose and brecciated serpentine with slickensides	ibid.
*	213	prasinitic breccia impregnated with pyrite (schalstein)	,,
	214	conglomerate with elements of prasinite, sandstone and chert	,,
*	215	nephritic actionolite-clinozoisite-schi$_{\omega}$t	S.Dadong, Darvel Bay (cf. Enclosure IX)
*	216	schistose plagioclase-hornblende-clinozoisite-gneiss	ibid.
	217	ophicalcite	Lower Segama
	218	decomposed spilite with amygdules of calcite	ibid.
*	219	fine-grained brecciated plagioclase-hornblende-schist	Pulau Sakar, Darvel Bay (cf. Enclosure VIII)
*	220	brecciated chlorite-magnetite-schist	ibid.
*	221	phyllite with accessory garnet	,,
*	222	streaky saussurite-amphibolite	,,
	223	schistose serpentine	,,
	224	scoria (artificial?)	,,
*	225	serpentinized dunite, actinolite-bearing	S.Diwata, Darvel Bay
*	226	serpentinized dunite	ibid.
*	227	antigorite-serpentine	,,
	228	schistose serpentine with slickensides	,,
*	229	uralit-gabbro, medium-grained, streaky	,,
*	230	adinole-slate	,,
*	231	chlorite-schist	,,
	232	conglomerate with elements of amphibolite, sandstone, chert and limestone	S.Segannen, Darvel Bay
	233	conglomerate with elements of amphibolite, sandstone and chert	S.Silibukan, Darvel Bay
*	234	pilotaxitic augite-labradorite-andesite with microlites of pigeonite-augite, boulder of volcanic agglomerate	ibid.

SAMPLES COLLECTED BY P. LEICESTER (L.), 1936

			Dent Peninsula, SE. coast of B.N.B. (cf. Enclosure VIII)
*L.	95	actinolite-schist	S.Telewas, right-hand tributary of Segama
*	97	actinolite-talc-chlorite-schist	ibid.
	102	decomposed diorite, medium-grained	S.Segama, upstream Kuala Telewas
†*	103	hornblende-quartz-diorite, medium-grained	ibid.
*	105	brecciated schalstein	,,

L.	106	spilite	S. Segama, upstream Kuala Telewas
*	109	foraminiferal limestone, Te_5-f	ibid.
*	120	hornblende-quartz-diorite	,,
*	121	mela-diorite, fine-grained	,,
*	122	hornblende-diorite, medium-grained	,,
*	124	calcareous andesitic tuffite-breccia, with vitrophyric lapilli and pyroxene crystals as main volcanic elements with foraminifera, Te_{2-5}	,,
	131	spilite	Lower Segama
	132	harzburgitic serpentine, decomposed	ibid.
*	135	actinolite-muscovite-schist, garnet and clinozoisite-bearing	,,
	178	spilite	,,
			Darvel Bay region
	190	andesite	E. cape of Pulau Timbun Mata
	191	andesitic tuffitic agglomerate	small island 2 km. S. of Simporna
*	192	vesicular hyalopilitic hypersthene-augite-labradorite-andesite	ibid.
*	194	plagioclase-hornblende-hornfels, fine-grained	small island 15 km. ESE. of Kuala Tingkayu
*	195	pyroxenite, fine-grained grey-green, olivine-bearing, with slickensides	Silam, W. of P. Sakar
	208	andesite	halfway between K. Silibukan and K. Tungku
*	211	hyalopilitic hypersthene-bearing augite-andesite with microlites of pigeonite-augite	ibid.

SAMPLES COLLECTED BY E. WENK (Wk.), 1936–1939

*Wk.	1	basalt	**INTERIOR,** S.Kuamut, N. of Tutuan
*	2	dark shale	S.Sapulut, near Kg. Sapulut
*	3p	uralite-diabase	S.Sinoa (Milian)
*	4p	ophitic diabase	ibid.
*	5p	porphyritic hornblende-microgranodiorite, altered, biotite-chlorite- and carbonate-bearing	,,
*	6p	*idem*, slightly altered, chlorite-bearing	,,
*	7p	*idem*, altered, rich in chlorite and carbonate	,,
*	8p	*idem*	,,
*	9p	*idem*	,,
*	10p	lherzolite	,,
*	11	quartzite	**SOUTH-EAST COAST,** S.Tiagau
*	12p	olivine-gabbro	**INTERIOR,** S.Kuamut, Kuala Imbok
*	13p	olivine-gabbro	ibid.
*	14p	hyalopilitic basalt or andesite, augite- and hypersthene-bearing, rich in glass	**EAST COAST,** Dent Peninsula, S.Mungkuou
*	15p	dunite, plagioclase-bearing, serpentinized	**INTERIOR,** S.Kuamut, Kuala Malog
*	16p	troctolite	ibid.
*	17p	harzburgite-serpentine	,,
*	18p	troctolite	,,
*	19p	olivine-gabbro	,,
*	20p	troctolite	,,
*	21p	troctolite	,,
*	22p	uralite-saussurite-albite-gabbro	**EAST COAST,** Dent Peninsula, S.Sebahat
*	23a	amygdaloidal spilite	**NORTH-EAST COAST,** P. Liheiman, mud-volcano
*	23b	scoriaceous spilite	ibid.
*	23c	vesicular spilite	,,
*	24	streaky fluidal hyalopilitic augite-hypersthene-hornblende-labradorite-andesite, ground-mass rich in hematite with microlites of pigeonite-augite	**SOUTH-EAST COAST,** W. of P. Nunukan, Tg. Tidung
*	25	*idem*	ibid.
*	26	hyalopilitic augite-hypersthene-labradorite-andesite	,,
*	27	*idem*, with microlites of pigeonite-augite	,,
*	28	*idem*, fluidal	,,

*Wk.	29	*idem*, with microlites of pigeonite-augite	W. of P. Nunukan, Tg. Tidung Salang
*	30	*idem*, fluidal with resorbed hornblende phenocrysts and microlites of pigeonite-augite	„ „ P. Sikapal
*	31	gabbro, hydrothermally altered	**INTERIOR,** S.Karamuak, S.Korong (copper mine)
*	32	olivine-gabbro	ibid.
			EAST COAST, Dent Peninsula
†*	33p	hyalopilitic hornblende-labradorite-andesite, biotite-bearing	S.Mungkuou
*	34p	carinthine-eclogite	„
*	35p	porphyritic hornblende-micro-quartz-diorite	„
*	36p	hyalopilitic augite-labradorite-andesite with resorbed hornblende phenocrysts and microlites of pigeonite-augite	„
*	37p	hyalopilitic diopside-labradorite-andesite	„
*	38p	fluidal hyalopilitic augite-labradorite-andesite with microlites of pigeonite-augite	„
*	39p	carinthine-eclogite	„
*	40p	hyalopilitic hornblende-biotite-labradorite-andesite, rich in glass, with amygdules of quartz	„
*	41p	hyalopilitic-pilotaxitic augite-labradorite-andesite, hypersthene-bearing, rich in pyrite	„
*	42p	salite-edenite-hornfels, labradorite- and spinel-bearing	„
*	43p	hyalopilitic hypersthene-augite-bytownite-andesite = miharaite	„
*	44p	hornblende-plagioclase-gneiss, garnet-bearing	„
*	45p	amphibolite	„
*	46p	amphibolite	„
*	47p	carinthine-eclogite	„
*	48p	hornblende-plagioclase-gneiss epidote-bearing	„
*	49p	amphibolite, pyroxene-bearing	S.Pungulupi
*	50	hyalopilitic augite-hypersthene-labradorite-andesite	„
*	51	zoisite-amphibolite, plagioclase-bearing	„
*	52	zoisite-amphibolite	„
*	53	carinthine-eclogite	„
*	54	carinthine-eclogite, feldspathized	„
*	55	amphibolite	„
*	56	diabase-porphyrite	„
*	57	carinthine-eclogite	„
*	58	hyalopilitic hornblende-augite-labradorite-andesite with microlites of pigeonite-augite	S.Tungku
*	59	mela-diorite	„
*	60	hyalopilitic augite-hornblende-labradorite-andesite, hypersthene-bearing, hornblende largely resorbed, tridymite in ground-mass	„
*	61	hyalopilitic hornblende-biotite-labradorite-andesite, with amygdules of quartz and with tridymite in ground-mass	S.Tungku
*	62	mela-diorite	„
*	63	radiolarian chert	„
			WEST COAST (cf. Enclosure VI)
*	64	porphyritic hornblende-biotite-micro-quartz-monzonite	Mt. Kinabalu, summit Low's Peak
†*	65	quartz-dioritic inclusion in granodiorite, rich in hornblende	„ summit plateau
†*	66	medium-grained hornblende-biotite-granodiorite	„ „
*	67	porphyritic quartz-monzonite-aplite	„ „
*	68	porphyritic biotite-hornblende-micro-quartz-monzonite	„ Sayat-Sayat
*	69	biotite-diopside-granodiorite-porphyry	„ below summit plateau
*	70	inclusion in diopside-bearing border facies, rich in amphibole and epidote	„ „ „
*	71	*idem*, rich in epidote and chlorite	„ „ „

*Wk.	72	porphyritic hornblende-biotite-micro-quartz-monzonite	Mt. Kinabula, 500 m. below summit
*	73	*idem*, weathered	„ below Paka cave
*	74	actinolite-peridotite	„ between Paka and Kamburonga
*	75	hornblende-biotite-granodiorite-porphyry, altered, chlorite- and carbonate-bearing	S.Mantaranau, near Bongol
*	76	hornblende-biotite-granodiorite-porphyrry	„ „
*	77	indurated shale	Mt. Kinabalu, below Lumu-Lumu
*	78	medium-grained hornblende-biotite-quartz-monzonite with aplite dyke	S.Kadamayan (Tampasuk) near Kiau
*	79	quartzite	„ „ „
*	80	quartzite	„ „ „
*	81	metamorphic spilite-breccia	„ „ „
*	82	metamorphic spilite-breccia	„ „ „
*	83	medium-grained hornblende-biotite-quartz-monzonite	S.Labong (Tampasuk) above Koung
*	84	porphyritic hornblende-biotite-quartz-monzonite with beginning micro-granitic texture	„ „ „
*	85	porphyritic hornblende-biotite-micro-quartz-monzonite	Kg. Labong-Labong (Tampasuk)
*	86	hornblende-microgranodiorite, altered	ibid.
*	87	metamorphic spilite-breccia	S.Kadamayan (Tampasuk) near Koung
*	88	serpentine, calcified	ibid.
*	89	metamorphic spilite breccia	„
			EAST COAST, Dent Peninsula
*	90	fluidal hyalopilitic augite-labradorite-andesite	S.Tungku
*	91	hyalopilitic-hyaline augite-bytownite-andesite, carbonate-bearing, rich in plagioclase	„
*	92	zoisite-amphibolite	
*	93	dunite-serpentine, silicified, ore-bearing	„
*	94	hyalopilitic-hyaline hornblende-labradorite-andesite with microlites of pigeonite-augite, groundmass rich in tridymite	„
*	95	schalstein	„
*	96	hyalopilitic-intergranular augite-labradorite-andesite	„
*	97	hyalopilitic labradorite-andesite, augite-, hypersthene- and resorbed hornblende-bearing, rich in glass	„
*	98	serpentine, silicified	„
*	99	hyalopilitic augite-labradorite-andesite with microlites of pigeonite-augite, ground-mass rich in haematite and glass	„
*	100	andesitic breccia	„
*	101	medium-grained andesitic crystal-tuff, matrix of Tungku volcanic conglomerate	„
*	102	hyalopilitic-pilotaxitic augite-labradorite-andesite, hypersthene-bearing, with microlites of pigeonite-augite	„
*	103	medium-grained andesitic crystal-tuff, matrix of Tungku volcanic conglomerate	„
*	104	foraminiferal, slightly calcareous andesitic tuffite-breccia, matrix of Tungku volcanic conglomerate	„
*	105	hyalopilitic hornblende-bytownite-andesite, augite- and hypersthene-bearing	„
*	106	pilotaxitic-hypocrystalline augite-hypersthene-bytownite-andesite (miharaite) with microlites of pigeonite-augite	„
*	107	pilotaxitic-hypocrystalline augite-labradorite-andesite	„
*	108	indurated red shale with veinlets and lenses of carbonate	mud-volcano Rasang
*	109	conglomeratic sandstone with well-rounded fragments of radiolarian chert in a sandy calcareous matrix rich in lithothamnia	ibid.

*Wk.	110	hyalopilitic (diopsidic) augite-labradorite-andesite, resorbed hornblende-bearing, rich in ore	S.Mungkuou
	111	serpentine	Kinabatangan, S.Tanigang
*	128	harzburgite-serpentine, calcified and silicified	,, S.Sukau
*	153a	serpentine	Kinabatangan delta, Bt. Laua Laua
*	153b	harzburgite-serpentine	ibid.
	449	calcareous argillaceous sandstone with pyrite	Dent Peninsula, Tagai Ulu Tabin
	586	ore sample with pyrite and chalcopyrite	INTERIOR, S.Karamuak, S.Korong "copper mine"

APPENDIX II

Tabulation of Determinations of Larger Foraminifera by I. M. van der Vlerk

SINCE it is one of the main objects of this paper to pass on to future explorers and to scientists interested in the geology of the East Indian Archipelago all exact information so far acquired, it has been thought necessary to publish a complete list of the macro-foraminiferal samples examined from North Borneo. These samples have revealed certain palaeontological key beds which have been helpful in the geological survey in a manner similar to that in which the astro-fixes have served the topographical survey. If in future some stratigraphical correlation should appear to be incorrect, the reviser, with the earlier data at his disposal, will be able to make the necessary adjustments.

The following tables provide a complete list of the samples from North Borneo which have been submitted to Prof. I. M. van der Vlerk in Leiden for determination of the larger foraminifera present and consequent determination of age. These include collections made by geologists both of the Shell Company of British North Borneo and of the Nederlandsche Koloniale Petroleum Maatschappij. Some work on material collected by the latter group was previously published by L. M. R. Rutten (1915, 1921, 1925); most of these samples have been re-examined by Prof. van der Vlerk.

The information given in the tables for each sample includes the number assigned by the collector, the locality, the foraminiferal assemblage determined and the age indication. The locations of the samples collected on the Kudat Peninsula and the northern islands are shown on the 1:100,000 maps which constitute Enclosures III and IV to this publication. All age indications are given on the 1:500,000 map (Enclosure I). The tabulation has been split into the following districts:

1. Balambangan, Banggi and adjacent islands.
2. Kudat and Bengkoka peninsulas (northern B.N.B.).
3. Klias Peninsula (western B.N.B.).
4. Interior and Kinabatangan area.
5. Segama area, Dent and Simporna peninsulas (eastern B.N.B.).
6. Sarudong-Kalabakang area (south-eastern B.N.B.).

Within each district the samples are arranged beginning with the northern- and western-most and continuing southwards and eastwards.

In our discussion of the formational correlations and micropalaeontology of the Tertiary sediments it was mentioned that subdivision and regional correlation of the Tertiary is based on the range of the larger foraminifera. No exact correlation with European series is yet possible, so the letter classification introduced by I. M. van der Vlerk and J. H. F. Umbgrove (1927) in the revised form suggested by W. Leupold and I. M. van der Vlerk (1931) was used in this paper on the geology of North Borneo. It has been assumed that the ranges of the foraminiferal genera and species established in the Netherlands East Indies are generally applicable to North Borneo. It must, however, be pointed out that, in limestone samples from the Kudat and Bengkoka peninsulas, and from the upper Segama region, a number of genera, which

are not believed to have common ranges, occur together. Thus certain limestones from these areas yielded both *Lepidocyclinae* assemblages diagnostic for Tertiary e and *Discocyclina* as well as *Pellatispira* typical of Tertiary a-b. In some of these cases mechanical admixture of older Tertiary and pre-Tertiary rock fragments was noticed by the field-geologist and admixture of probably Cretaceous globigerina chalk and radiolarian chert as well as basic igneous rocks of the Danau Formation, was evident from microscopic study. In other instances, such re-working was not immediately apparent, and the presumed autochthonous fauna was previously regarded as of Tertiary c-e age. Later investigations of these samples with mixed faunas have led to the conclusion that in most cases some evidence of re-deposition can be traced and consequently re-working has been supposed to account for the presence of the older forms. But the possibility of normally Tertiary a-b and Tertiary late e forms having lived contemporaneously in the Tertiary c-e seas of North Borneo cannot be overlooked and should be checked by future work.

Recently M. G. Rutten (1948) re-examined one of the foraminiferal limestone samples from British North Borneo and concluded that its fauna is not homogeneous, but consists of a number of genera typical of the East Indian Neogene, together with re-deposited specimens from the Eocene.

Assuming the conception of the re-deposition of re-worked foraminiferal material is correct, it cannot be excluded that in a certain locality only a re-worked older fauna is deposited and elements of the younger fauna are missing. In such a case the age determination will only be based on the presence of, say, Ta-b forms, whereas for stratigraphical reasons the sediments containing this fauna have to be considered as Te. As a matter of fact this is the case with several samples from Te sediments collected in the Kudat and Bengkoka peninsulas. As no detailed descriptions of these samples are available, it is impossible to decide whether the faunas contained therein are re-worked, but on the basis of the presence of other samples with a mixed assemblage, a Te age of the series in question is assumed.

1. BALAMBANGAN, BANGGI AND ADJACENT ISLANDS

(cf. Enclosure III)

a. P. BALAMBANGAN

1. Ba. 227, SW. coast
   Lepidocyclina (*Trybliolepidina*) *martini* *Schlumb*
   Miogypsina sp. (with lateral chambers)
   Cycloclypeus sp.
   Tf_{1-3}, probably f_3
2. Ba. 228, SW. coast
   Globigerina sp.
   Gypsina globulus Reuss
   Cyclopeus sp.
   Lepidocyclina (*Nephrolepidina*) *angulosa* Prov.
   Lepidocyclina (*Trybliolepidina*) *rutteni* v.d. Vlerk
   Miogypsina sp. (with lateral chambers)
   Tf_{1-2}
3. Ba. 164, S. coast
   Lepidocyclina (*Nephrolepidina*) *ferreroi* Prov.
   Lepidocyclina (*Nephrolepidina*) *callosa* Scheffen
   Miogypsina sp. (with lateral chambers)
   Te_5-f_2, probably Tf_{1-2}
4. H. 58, reef off S. point, Tg. Kalutan
   Carpenteria sp.
   Cycloclypeus sp.
   Spiroclypeus sp.
   Lepidocyclina (*Eulepidina*) sp.
   ,, (*Nephrolepidina*) sp.
   Miogypsina (*Miogypsinoïdes*) sp.
   Te_{4-5}
5. Ba. 161, S. Balambangan
   Globigerina sp.
   Amphistegina lessonii d'Orb
   Cycloclypeus sp.
   Lepidocyclina (*Nephrolepidina*) *angulosa* Prov.
   Lepidocyclina (*Eulepidina*) sp.
   Te_{3-5}
6. Ba. 167, S. coast
   Globigerina sp.
   Amphistegina lessonii d'Orb
   Lepidocyclina (*Nephro* or *Trybliolepidina*) sp.
   Te-f, probably Tf
7. Ba. 165, S.Balambangan
   Miliolina sp.
   Globigerina sp.
   Rotalia sp.
   Amphistegina lessonii d'Orb
   Spiroclypeus sp.
   Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
   Te_{2-5}
8. Ba.165a, S.Balambangan
   Miogypsina sp. (with lateral chambers)
   Te_5-f, probably Tf
9. Ba. 162, S.Balambangan
   Globigerina sp.
   Carpenteria sp.
   Amphistegina lessonii d'Orb
   Cycloclypeus sp.
   Lepidocyclina (*Eulepidina*) sp.

9. Ba. 162, S. Balambangam (*continued*)
Lepidocyclina (*Nephrolepidina*) *angulosa* Prov.
Lepidocyclina (*Nephrolepidina*) *ferreroi* Prov.
Lepidocyclina (*Nephrolepidina*) *sumatrensis* Brady
Te_5
10. Ba. 177, SW. coast, Batu Lingin
Globigerina sp.
Amphistegina lessonii d'Orb
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Lepidocyclina (*Trybliolepidina*) *rutteni* v. d. Vlerk
Tf
11. Ba. 220, SW. coast
Lepidocyclina (*Nephro* -or *Trybliolepidina*) sp.
Miogypsina sp. (with lateral chambers)
Te-f, probably Tf

b. P. BANGGI AND ADJACENT ISLANDS

12. N. 2157, P. Banggi, W. coast
Discocyclina sp.
Ta-b
13. H. 45, P. Banggi, W. coast
Gypsina globulus Reuss
Carpenteria sp.
Cycloclypeus sp.
Operculinella venosa (F. et M.)
Lepidocyclina (*Nephrolepidina*) sp.
„ („) *sumatrensis* Brady
Miogypsina (*Miogypsinoïdes*) sp.
Te_5-f_2
14. N. 2110, P. Banggi, W. coast
Globigerina sp.
Carpenteria sp.
Lepidocyclina (*Nephro-* or *Trybliolepidina*) sp.
Te-f, probably Tf
15. G. 2108, P. Banggi, W. coast
Camerina sp.
Discocyclina sp.
Ta-b, probably Tb
16. G. 2090, P. Banggi, SW. corner
Gypsina globulus Reuss
Carpenteria sp.
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Spiroclypeus leupoldi v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) sp.
Miogypsina dehaarti v. d. Vlerk
Te_4-$_5$
17. G. 2085, P. Banggi, SW. corner
Heterostegina borneënsis Prov.
Spiroclypeus leupoldi v. d. Vlerk
Lepidocyclina (*Nephrolepidina*) *sumatrensis* Brady
Lepidocyclina (*Trybliolepidina*) *transiens* Umbgr.
Miogypsina dehaarti v. d. Vlerk
Te_4
18. S. 50, P. Meriangin Kechil
Carpenteria sp.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Lepidocyclina (*Nephrolepidina*) cf. *borneensis* Prov.
Miogypsina sp. (with lateral chambers)
Tf, probably Tf_1
19. S. 51 P. Meriangin Kechil, S. coast
Carpenteria sp.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Miogypsina sp. (with lateral chambers)
Tf
20. S. 157, P. Meriangin Besar, E. corner
Carpenteria sp.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Tf
21. I. 1, P. Patanunan
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Tf, probably Tf_3
22. I. 2, P. Patanunan
Cycloclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp.
„ (*Trybliolepidina*) *rutteni* v. d. Vlerk
Tf
23. I. 13, Batu Puteh, S. of P. Banggi
Carpenteria sp.
Cycloclypeus sp.
Spiroclypeus leupoldi v. d. Vlerk
Lepidocyclina (*Nephro-* and *Eulepidina*) sp. sp.
Miogypsina dehaarti v. d. Vlerk
Te_1-$_5$, probably Te_4
24. M. 11, rocky island off P. Balak
Operculinella venosa (F. et M.)
Gypsina globulus Reuss
Cycloclypeus sp.
Heterostegina sp.
Lepidocyclina (*Eulepidina*) sp.
Te
25. H. 1, P. Balak, SW. corner
Amphistegina lessonii d'Orb
Operculina sp.
Carpenteria sp.
Cycloclypeus sp.
Lepidocyclina (*Nephrolepidina* and/or *Trybliolepidina*) sp. sp.
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf
26. I. 15, P. Balak, SW. corner
Carpenteria sp.
Cycloclypeus sp.
Lepidocyclina Trybliolepidina) sp.
„ (*Nephrolepidina*) *sumatrensis* Brady
Miogypsina sp. (with lateral chambers)
Te_5-f_2, probably Tf_1-$_2$
27. A, P. Balak, SW. corner
Gypsina globulus Reuss
Amphistegina lessonii d'Orb
Cycloclypeus sp.

27. A, P. Balak, SW. corner (*continued*)
Lepidocyclina cf. (*Nephrolepidina*) *sumatrensis* Brady
Te-f, probably Te_1-f_2

28. N. 2670, P. Banggi, Bt. Timbang Dayang
Carpenteria sp.
Cyloclypeus sp.
Lepidocyclina (*Trybliolepidina*) *rutteni* v. d. Vlerk
Miogypsina sp. (with lateral chambers)
Tf

29. H. 2, P. Banggi S. coast, N. of P. Pagasan
Carpenteria sp.
Operculinella sp.
Cycloclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp.
„ (*Trybliolepidina*) *rutteni* v. d. Vlerk
Te-f, probably Tf

30. I. 14, P. Balak, NE. corner
Globigerina sp.
Amphistegina lessonii d'Orb
Carpenteria sp.
Cycloclypeus (*sectio Carpenteri* Brady) sp.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Miogypsina sp. (with lateral chambers)
Tf_2-$_3$

31. I. 19, P. Modom
Heterostegina sp.

31. I. 19, P. Modom (*continued*)
Camerina sp.
Discocyclina (*Discocyclina*) sp.
„ (*Asterocyclina*) sp.
Pellatispina madaraszi Hautk. var. *provalei* Yabe
Ta-b, probably Tb

32. H. 71, P. Banggi, Upper S.Sibumbung
Carpenteria sp.
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *angulosa* Prov.
Lepidocyclina sp.
Te_3-$_5$

33. G. 2320, 2321 P. Banggi, N. coast, E. of S.Sibumbung
Camerina sp.
Heterostegina sp.
Discocyclina umbilicata Defr.
Ta-b, probably Tb

34. H. 22, P. Manawali, off W. coast
Amphistegina lessonii d'Orb
Amphistegina or *Heterostegina*
Lepidocyclina (*Nephrolepidina* or *Trybliolepidina*) sp.
Te-f, probably Tf
Further samples from Balambangan and Banggi Islands are described by Rutten (1915).

2. KUDAT AND BENGKOKA

(cf. Enclosure IV)

a. KUDAT PENINSULA

35. Nh. 40, path from Kg. Labuan Sekrotang to Kg. Tomagung, northernmost part of the peninsula
Camerina thalicus L. M. Davies
Discocyclina sp.
Ta-b

36. Nh. 1, P. Kelambu (Labuan Sekrotang), NW. coast
Operculinella venosa (F. et M.)
Heterostegina or *Spiroclypeus*
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *borneënsis* Prov.
Te_2-$_5$

37. S. 11, S.Loro Kechil, NW. coast
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Lepidocyclina (*Nephrolepidina*) *borneënsis* Prov.
Miogypsina sp. (with lateral chambers)
Te_5

38. Nh. 4, Tg. Loro, NW. coast
Operculina sp.
Gypsina sp.
Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Te

39. Nh. 5, Tg. Loro, NW. coast
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) *dilatata* Mich.
„ sp. (microspheric)
Te_2

40. S. 10, Tg. Loro, NW. coast
Neoalveolina pygmaea (Verbeek)
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
„ (*Eulepidina*) sp.
Lepidocyclina (*Trybliolepidina*) *transiens* Umbgr.
Te_1-$_3$

41. Nh. 34, SE. of Tg. Bangau, NW. coast
Spiroclypeus tidoenganensis v. d. Vlerk
Lepidocyclina (*Eulepidina*) *atuberculata* v. d. Vlerk
Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Lepidocyclina flexuosa Rutten
Miogypsina (*Miogypsinoïdes complanata* Schlumb var. *bantamensis* Tan.
Te_4

42. Nh. 35, SE. of Tg. Bangau, NW. coast
Camerina sp.
Spiroclypeus sp.

42. Nh. 45, SE. of Tg. Bangau, NW. coast (*continued*)
Discocyclina sp.
Te_{3}-$_{5}$ (+b); brecciated limestone, older foraminifera probably washed in

43. Nh. 56, Upper S.Bumbum, on path Sequati-Tomagong
Cycloclypeus or *Heterostegina*
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Te

44. Nh. 51, Lower S.Bumbum, WNW. of Kudat
Heterostegina sp.
Spiroclypeus pleurocentralis (Carter)
„ *tidoenganensis* v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Miogypsina (*Miogypninoïdes*) sp.
Te_{4}(+b). According to L. Rutten (1925a, pp. 420, 421) this brecciated limestone sample with fragments of chert contains also *Nummulina* and *Pellatispira*.*

45. T. 123, Lower S.Bumbum, road Kudat-Sequati
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ „ *dilatata* Mich.
„ sp. (microspheric)
besides several reworked specimens of the old Tertiary
Pellatispira inflata U bgr.
Te_{2}(+b)

46. T. 77, Road Kudat-Sequati, N. of Kuala Bumbum
Cycloclypeus sp.
Spiroclypeus leupoldi v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) sp.
Miogypsina sp. (with lateral chambers)
Te_{5}

47. Nh. 49, Estate Broese, 2·5 km. NW. of Kudat
Cycloclypeus sp.
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Miogypsina (*Miogypsina*) sp.
Te_{5}

48. Rh. 3, Estate Broese NW. of Kudat
Camerina sp.
Cycloclypeus sp.
Pellatispira sp.
Discocyclina sp.
Lepidocyclina sp.
„ (*Neprholepidina*) *verrucosa* Schlumb
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoïdes*) sp.
Te_{5}-f_{2}(+b); brecciated limestone with fragments of older rocks, the Eocene foraminifera are probably washed in.

*According to recent investigations by M. G. Rutten 1948) the sample Nh. 51 contains, apart from the Miocene forms mentioned above, the following genera characteristic of the Eocene: *Lockhartia*, *Nummulites*, *Biplanispira*, and *Discocyclina* (*Aktinocyclina*).

49. Rh. 4, Estate Broese NW. of Kudat
Cycloclypeus sp.
Spiroclypeus sp.
Camerina sp.
Pellatispira sp.
Lepidocyclina sp.
„ (*Eulepidina*) sp.
Miogypsina (*Miogypsinoïdes*) sp.
Te_{3}-$_{5}$(+b); brecciated limestone with fragments of older rocks, the Eocene foraminifera are probably washed in.

50. S. 14, Tg. Kapor, N. of Kudat, NE. coast
Neoalveolina pygmaea (Verb.)
Carpenteria sp.
Gypsina globulus Reuss
Lepidocyclina sp.
„ (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Miogypsina sp. (with lateral chambers)
„ (without lateral chambers)
Discocyclina sp. (probably some washed in examples as well as fragments of perhaps Cretaceous *globigerina* chalk)
Te_{5}(+b)
The samples Nh.34, 35, 56, 51, T.123, 77, Nh.49, Rh.3, 4 and S.14 appear to derive from the same limestone zone stretching from the west to the east coast of the peninsula and bordering the pre-Tertiary uplift of Bangau-Agung Agung (see Enclosure IV)

51. T. 13, Lower road Kudat
several fragments of small *Lepidocyclina* and *Miogypsina*
Te_{5}-f

52. Rh. 30, Near Residency of Kudat
Gypsina globulus Reuss
Heterostegina borneënsis v. d. Vlerk
Pellatispira sp.
Discocyclina sp.
Lepidocyclina sp.
„ (*Eulepidina*) sp.
Te_{1}-$_{4}$(+b); the Eocene foraminifera are probably washed in.

53. Rh. 8, Beach near Kudat
Carpenteria sp.
Heterostegina sp.
Spiroclypeus sp.
Gypsina globulus Reuss
Discocyclina sp.
Lepidocyclina (*Nephrolepidina*) *verrucosa* Schlumb
Lepidocyclina (*Nephrolepidina*) *sumatrensis* Brady
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoïdes*) sp.
Te_{5}(+b); brecciated limestone with fragments of older rocks, the Eocene foraminifera are probably washed in.

54. Rh. 16, South coast of Kudat Harbour near Tigasamil
Heterostegina or *Cycloclypeus*
Spiroclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp.

54. Rh. 16, South coast of Kudat Harbour near Tigasamil (*continued*)
Discocyclina sp.
Lepidocyclina (*Nephrolepidina*) sp.
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoïdes*) sp.
Te_5(+b); fragments of older rocks, the Eocene foraminifera are probably washed in.

55. Nh. 61, east of Kg. Dualog, central part of the peninsula
Lepidocyclina sp. sp.
Miogypsina (*Miogypsinoïdes*) sp.
Te_4-f_2

56. Nh. 60, S.Dualog, SE. of Kg. Mirbau, central part of the peninsula
Camerina sp.
Pellatispira sp.
Heterostegina sp.
Spiroclypeus sp.
Lepidocyclina sp.
Discocyclina sp.
Te_{2-5}(+b); limestone-breccia with fragments of probably Cretaceous rock, older foraminifera probably washed in.

57. M. 56, bridle path near S.Dualog (probably the same locality as Nh. 60)
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Discocyclina sp. (fragments)
Te_{2-5}(+b); brecciated limestone with inclusions of *Globigerina* chalk (probably of Cretaceous age)

58. M. 29, Dumpirit, SW. of Kudat Bay
Neoalveolina pygmaea (Verbeek)
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Further re-worked fragments of *Pellatispira* and *Discocyclina* and of a possibly Cretaceous *Globigerina* chalk
Te_{1-3}(+b)

59. M. 23, bridle path SW. of Kudat Bay
Trillina howchini Schlumb
Neoalveolina pygmaea (Verbeek)
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
and one single specimen of re-worked *Discocyclina*
Te_{1-3}(+b)

60. Nh. 130, Tg. Taburan Tamid, west coast
Camerina sp.
Discocyclina (*Discocyclina*) sp.
„ (*Asterocyclina*) sp.
calcareous sandstone with fragments of an older rock
Tb

61. Nh. 136, south of Kg. Nangkak, east coast of Kudat Peninsula
Operculinella sp.
Spiroclypeus sp.

61. Nh. 136, south of Kg. Nangkak, east coast of Kudat Peninsula (*continued*)
Lepidocyclina sp.
Miogypsina (*Miogypsinoïdes*) sp.
as well as fragments of an older rock
Te_{4-5}

62. Nh. 139, south of Kg. Nangkak and the telegraph line Kudat-Langkom, east coast of Kudat Peninsula
Heterostegina sp.
Spiroclypeus sp.
Lepidocyclina sp.
Te_{2-5}

63. Nh. 140, S.Bengkongan, N. of Langkom, SW. of Marudu Bay
Operculina sp.
Lepidocyclina sp.
Discocyclina sp.
Td-f (+b) (*Discocyclina* probably washed in)

64. Nh. 143, affluent of S.Mangaris, on the bridle path Langkom-Kota Belud
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Heterostegina sp.
Spiroclypeus sp.
Camerina sp.
Lepidocyclina sp.
Discocyclina sp.
Te_{2-5} (+b), conglomeratic limestone with fragments of older rocks, older foraminifera probably washed in

65. Nh. 149, bridle path Langkom-Kota Belud, headwaters of S.Mangaris
Neoalveolina pygmaea (Verbeek)
Lepidocyclina sp.
Spiroclypeus sp.
Further re-worked specimen of *Pellatispira* and *Discocyclina* and fragments of older rocks
Te_{2-5} (+b)

66. Nh. 154, upper S.Sungei, S. of Langkom, SW. of Marudu Bay
Alveolina sp.
„ (*Flosculina*) sp.
Camerina sp.
Discocyclina sp.
Ta-b

b. BENGKOKA PENINSULA

67. T. 70, Tg. Teburik, northernmost point of the peninsula
Neoalveolina pygmaea (Verbeek)
Lepidocyclina (*Eulepidina*) sp.
Miogypsina sp. v. d. Vlerk
Te_{3-4}

68. T. 90, Tg. Dundulik, north-east coast
Globigerina sp.
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb
Tf

69. S. 4433, head-waters of S.Lagatan, northern central part of the peninsula
Miliolina sp.
Orbulina universa d'Orb
Globigerina sp.
Textularia sp.
Operculinella venosa (F. et M.)
Carpenteria sp.
Pellatispira sp.
Spiroclypeus sp.
Cycloclypeus or *Heterostegina*
Linderina sp.
Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Discocyclina sp.
Te_{2-5} (+b); brecciated limestone with fragments of probably Mesozoic rocks; *Pellatispira* and *Discocyclina* are considered as having been re-worked

70. S. 4271, between the head-waters of S.Mangkubau and Melobang Bay, northern-central part of the peninsula
Globigerina sp.
Neoalveolina pygmaea (Verbeek)
Rotalia sp.
Carpenteria sp.
Operculinella venosa (F. et M.)

70. S. 4271, between the head-waters of S.Mangkubau (*continued*)
Pellatispira sp.
Spiroclypeus sp.
Cycloclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Miogypsina (*Miogypsina*) sp.
Te_5 (+b); brecciated limestone with fragments of probably Mesozoic rock; the foraminifera, extinct in e_5 times must be re-worked

71. S. 53, Melobang Bay, Tg. Puteh, north-west coast of the peninsula
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Spiroclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp.
„ (*Eulepidina*) sp.
Miogypsina sp. (with lateral chambers)
Further, a few specimens of *Discocyclina* sp., probably re-worked, and inclusions of a possibly Cretaceous *Globigerina* chalk
Te_5 (+b)

72. S. 270, Tg. Pengali, Paitan Bay
Camerina cf. *divina* Doornink
Discocyclina sp.
Ta-b

3. KLIAS PENINSULA

73. Rh. 1, Tg. Nosong
Operculinella sp.
Spiroclypeus sp.
Lepidocyclina sp.
Te_{2-5}

74. Nh. 499, S.Siliko
Carpenteria sp.
Operculinella venosa (F. et M.)
Spiroclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp. sp.
Miogypsina sp.

74. Nh. 499, S.Siliko (*continued*)
Te_{4-5}

75. H. 115, "New Island", SW. coast of Klias Peninsula
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
„ sp.
Operculinella venosa (F. et M.)
Te_{1-3}

4. INTERIOR AND KINABATANGAN AREA

a. PEGALAN AREA (north-western-central part of B.N.B.)

76. Nh. 336, S.Pangas, tributary of S.Pegalan
Camerina sp.
Discocyclina sp.
Ta-b

b. SAPULUT-TALANGKAI AREA (southern-central part of B.N.B.)

77. RW.16, S.Sapulut, S. of Bt. Tambunan, Pangkalan Jalan Pinanga
Amphistegina lessonii d'Orb
Operculinella venosa (F. et M.)
Cycloclypeus eidae Tan
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina flexuosa Rutten
„ (*Eulepidina*) *formosa* Schlumb

77. RW.16, S.Sapulut, S. of Bt. Tambunan, Pangkalan Janan Pinanga (*continued*)
Lepidocyclina (*Nephrolepidina*) *isolepidinoides* v. d. Vlerk
Te_{1-3}

78. RW. 17, S.Sapulut, 2 km. N. of Batu Punggul
Carpenteria sp.
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
Te_{1-3}

79. RW. 18, Batu Punggul, S.Sapulut
Carpenteria sp.
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
Te_{1-3}

c. KINABATANGAN AREA (tabulation starting from head-waters)

80. RW. 15, S.Pinanga, N. of Anggi Anggi
Carpentaria sp.
Operculinella venosa (F. et M.)
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf

81. RW. 14, caves above S.Sinobang (branch of S.Pinanga)
Miliolina sp.
Carpenteria sp.
Lepidocyclina sp. (microspheric)
„ (*Nephro-* or *Trybliolepidina*) sp.
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf

82. RW. 13, Kogong, S.Pinanga
Amphistegina lessonii d'Orb
Heterostegina sp.
Lepidocyclina flexuosa Rutten
„ (*Nephrolepidina*) *douvillei* Yabe
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf

83. RW. 12, Kogong, S.Pinanga
Cycloclypeus sp.
Lepidocyclina sp. (microspherical)
„ (*Nephrolepidina*) *douvillei* Yabe
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf

84. RW. 11, S.Pinanga, E. of Kogong
Globigerina sp.
Carpenteria sp.
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Lepidocyclina sp. sp. (among others large microspherical species)
Lepidocyclina (*Nephrolepidina*) *sumatrensis* Brady
Miogypsina (*Miogypsina*) sp.
Te_5-f, probably Tf

85. RW. 10, S.Pinanga, upstream from Kuala Panaguan
Spiroclypeus sp.
Lepidocyclina sp. sp.
„ (*Eulepidina*) sp.
Te_{2-5}

86. RW. 9, S.Pinanga, Kuala Tudungin
Amphistegina lessonii d'Orb
Cycloclypeus or *Heterostegina* sp.
Heterostegina borneënsis v. d. Vlerk
Spiroclypeus leupoldi v. d. Vlerk
Lepidocyclina sp. sp.
„ (*Eulepidina*) sp.
Te_{2-5}

87. RW. 8, Bt. Sarupi, S.Milian, N. of Kg. Kuamut
Operculina sp.
Lepidocyclina (*Nephro-* or *Trybliolepidina*) sp.
Te-f

88. A, probably the same locality as RW. 8, S.Milian above Kuala Kuamut
Carpenteria sp.
Amphistegina sp.
Operculina sp.
Cycloclypeus sp.
Lepidocyclina sp.
Td-f

89 RW. 3, P. Tabakau in S.Kuamut
Carpenteria sp.
Gypsina globulus Reuss
Lepidocyclina flexuosa Rutten
„ (*Nephrolepidina*) *borneënsis* Prov.
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoïdes*) sp.
Te_4-f; sample 89 lies immediately above unconformity

90 WK. 791A, S.Bayudon-Napagun, tributary of S. Kuamut (boulder)
Operculina sp.
Miogypsina (*Miogypsina*) sp.
Te_5-f

91. RW. 6, Bt. Tigong, W. of Daramakod, Kinabatangan
Spiroclypeus sp.
Lepidocyclina (*Nephrolepidina*) cf. *borneënsis* Prov.
Te_{2-5}

92. RW. 7, Litukunup (Bt. Daramakod), Kinabatangan
Amphistegina lessonii d'Orb
Spiroclypeus sp.
Lepidocyclina sp. (small species)
Te_{2-5}
Samples RW. 8, A, RW. 6 and 7 derive from the same geological zone

93. RW. 24, Supu, Kinabatangan
Trillina howchini Schlumb
Alveolinella globulosa Rutten
Amphistegina lessonii d'Orb
Carpenteria sp.
Lepidocyclina cf. *angulosa*
Mioypsina (*Miogypsina*) sp.
Te_5-f

94. S. 282, Supu, Kinabatangan
Trillina howchini Schlumb
Carpenteria sp.
Amphistegina lessonii d'Orb
Spiroclypeus sp.
Lepidocyclina sp.
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoides*) *dehaarti* v. d. Vlerk
Te_{4-5}

95. RW. 25, Supu, Kinabatangan
Operculinella venosa (F. et M.)
Lepidocyclina (*Eulepidina*) *andrewsiana* J. et Ch.
Lepidocyclina (*Nephrolepidina*) *parva* Opp.
Miogypsina (*Miogypsina*) sp.
Te_4

96. S. 278, Batu Puteh, Kinabatangan
Carpenteria sp.
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Cycloclypeus sp.
Lepidocyclina (*Nephrolepidina*) sp.
Miogypsina sp.
Te_4

97. RW. 26, Bulud Batangan, Kinabatangan
Spiroclypeus pleurocentralis (Carter)
Lepidocyclina (*Eulepidina*) sp.
Te_{2-5}

98. RW. 20, Bukit Gumantong (base)
Miliolina sp.
Carpenteria sp.
Gypsina plana (Carter)
Miogypsina (*Miogypsinoïdes*) *dehaarti* v. d. Vlerk
Linderina paronao Prov.
Te_{4-5}

99. RW. 21, Bukit Gumantong, Lobang Muditam
Carpenteria sp.
Lepidocyclina (*Nephrolepidina*) *isolepidinoïdes* v. d. Vlerk
Miogypsina (*Miogypsinoïdes*) *dehaarti* v. d. Vlerk
Te_5

100. RW. 22, Bukit Gumantong (top)
Carpenteria sp.
Miogypsina (*Miogypsinoïdes*) *dehaarti* v. d. Vlerk
Te_{4-5}

101. S. 277, Bulud Batangan, Kinabatangan
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Gypsina globulus Reuss
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Cycloclypeus sp.
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
„ (*Nephrolepidina*) *borneënsis* Prov.
Te_{2-4}

102. RW. 19, Bukit Gaban, Kinabatangan
Amphistegina lessonii d'Orb
Carpenteria sp.
Spiroclypeus pleurocentralis (Carter)
Lepidocyclina (*Eulepidina*) sp.
„ cf. *borneënsis*
Te_{2-5}

103. RW. 23, S.Tanigang, tributary of Kinabatangan
Amphistegina lessonii d'Orb
Operculinella venosa (F. et M.)
Lepidocyclina (*Nephrolepidina*) *parva* Opp.
Miogypsina (*Miogypsinoïdes*) *dehaarti* v. d. Vlerk

103. RW. 23, S.Tanigang, tributary of Kinabatangan (*continued*)
Te_{4-5}

104. S. 275, Kuala Mananggol near Sukau, Kinabatangan
Amphistegina lessonii d'Orb
Cycloclypeus sp.
Spiroclypeus sp.
Lepidocyclina (*Nephrolepidina*) *angulosa* Prov.
Lepidocyclina (*Eulepidina*) sp.
Miogypsina (*Miogypsina*) sp.
Te_5

105. RW. 27, Kuala Mananggol near Sukau, Kinabatangan
Lepidocyclina (*Eulepidina*) sp.
Td-e

106. WK. 122, S.Sukau, tributary of Kinabatangan
Cycloclypeus sp.
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) *panata* Opp.
„ (*Nephrolepidina*) sp. sp.
Te_{1-3}

107. S. 274, Batu Tumanggong, Kinabatangan
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Lepidocyclina (*Eulepidina*) sp.
Te_{1-4}

108. S. 273, Batu Tumanggong, Kinabatangan
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
Te_{2-4}

109. RW. 28, Batu Tumanggong, Kinabatangan
Miliolina sp.
Neoalveolina pygmaea (Verbeek)
Carpenteria sp.
Amphistegina lessonii d'Orb
Linderina paronai Prov.
Cycloclypeus or *Heterostegina*
Lepidocyclina (*Nephrolepidina*) sp.
Te

110. S. 272, Tanjong Batu, Kinabatangan
Carpenteria sp.
Amphistegina lessonii d'Orb
Heterostegina borneënsis v. d. Vlerk
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
Te_{2-4}

111. RW. 29, Tanjong Batu, Kinabatangan
Miliolina sp.
Neoalveolina pygmaea (Verbeek)
Textularia sp.
Linderina paronai Prov.
Carpenteria sp.
Spiroclypeus sp.
Lepidocyclina (*Eulepidina*) sp.
Te_{2-5}

5. SEGAMA AREA, DENT AND SIMPORNA PENINSULAS

(see Enclosure VIII)

a. SEGAMA AREA

112. L. 124, S.Segama below Batu Selawak
Spiroclypeus sp.

112. L. 124, S.Segama below Baru Selawak (*continued*)
Operculinella sp.
Discocyclina sp. (re-worked)

112. L. 124 S.Segama below Baru Selawak (*continued*)
Te_{2-5} (+b); foraminiferal tuffite-breccia

113. L. 109, Kuala Mensuli
Globigerina sp. sp.
Lepidocyclina sp. (microspheric form)
„ (*Nephrolepidina*) *ferreroi* Prov.
Te_5-f

b. DENT PENINSULA

114. WK. 314, S.Biag Tagai, branch of S.Tungku
Alveolinella bontangensis Rutten
Amphisorus hemprichii Ehr.
Miogypsina (*Miogypsina*) *cushmani* Vaughan var. *indonesiensis* Tan.
Tf

115. WK. 304, S.Tungku, 1·1 km. SE. of Kuala Biag Tagai
Alveolinella bontangensis Rutten
fragment of some *Cycloclypeus*
Miogypsina (*Miogypsina*) *cushmani* Vaughan var. *indonesiensis* Tan.
Tf

116. T. 4833, Head-waters of S.Mungkuou (S.Rashleigh)
Neoalveolina melo (F. et M.)
Amphisorus hemprichii Ehr.
Lepidocyclina (*Trybliolepidina*) *martini* Schlumb

116. T. 4833, Head-waters of S.Mungkuou (S.Rashleigh (*continued*)
Tf

117. B, Lower course of S.Tungku
Marginopora vertebralis (Q. et G.)
Operculinella venosa (F. et M.)
T undet.

c. SIMPORNA PENINSULA

118. J. 206, S.Subahan, W. of Darvel Bay
Operculinella sp.
Spiroclypeus sp.
Lepidocyclina sp.
Te_{2-5}

119. R. 74, S.Klumpang
Alveolinella globulosa Rutten
Operculinella sp.
Heterostegina or *Cycloclypeus*
Lepidocyclina sp. (small species)
Miogypsina (*Miogypsina*) sp.
Tf

120. R. 74a, S.Klumpang
Carpenteria sp.
Heterostegina or *Cycloclypeus*
Lepidocyclina sp. (small species)
„ (? *Eulepidina*)
Miogypsina (*Miogypsina*) sp.
„ (*Miogypsinoïdes*) sp.
Te_5-f, probably Te_5

6. SARUDONG-KALABAKANG AREA

121. C. Head-waters of S.Kalabakang between Kuala Inapayat and Kuala Kalalatu
Operculinella venosa (F. et M.)
Lepidocyclina sp.
Miogypsina (*Miogypsina*) sp.
Te_5-f

122. D. Head-waters of S.Kalobang (tributary of S.Kalabakang)
Archaias angulatus (F. et M.)
Gypsina sp.
Amphistegina lessonii d'Orb
Lepidocyclina (*Nephrolepidina*) *angulosa* Prov.
„ „ *douvillei* Yabe

122. D. Head-waters of S.Kalobang (tributary of S.Kalabakang) (*continued*)
Lepidocyclina (*Nephrolepedina*) *isolepidinoïdes* v. d. Vlerk
Miogypsina (*Miogypsina*) *Kotoi* Haut. var. *bispiralis* Tan.
Te_5

123. E., Head-waters of S.Tambalunan (S.Sarudong)
Flosculinella bontangensis (Rutten)
Operculinella venosa ((F. et M.)
Te_5-f, probably Tf
Samples which did not contain diagnostic foraminifera are not tabulated

APPENDIX III

Micro-Palaeontological Examination of Some Calcareous Rock Samples from the Danau Formation

by

M. Reichel, University of Basel

The material examined comprised a batch of 11 samples, each accompanied by a few thin sections, consisting of limestones and hard, marly limestones, some of which were partially silicified. Their microfauna could not be extracted by washing. The pulverization to which a certain number of samples had been subjected before they reached us, did not yield any satisfactory results. The foraminifera, instead of being

isolated, remained attached to the rock particles and were mostly shattered to pieces. Under the binocular microscope, portions of them could be seen on the faces of the angular pulverized rock waste.

Silicified foraminifera which had been detached by erosion could be distinguished in places on the surface of samples H. 143 and H. 147, but their characters could no longer be clearly seen as the mineral transformation they had undergone had considerably altered their contours. Our determinations are therefore based mainly on observations made in thin-section.

The rocks in question contained either radiolaria or small foraminifera which were mostly pelagic. Unfortunately, no " large " foraminifera were found, apart from a fragment of *Camerina* in sample Nh. 52. The rocks therefore yielded few reliable stratigraphical guide fossils, and their age could not, for the most part, be determined exactly.

For purposes of description we can classify these samples, according to their microfauna, as follows:

(A) Radiolarian limestones, H. 7, 7a, 50, 75, St. 195.
(B) *Globorotalia* and *Globigerina* limestones, H. 142, 143, 144 and 147.
(C) *Globigerina* limestone without *Globorotalia*, Nh. 52, 514.

A. Radiolarian Limestones

H. 7: P. Batawan, E. coast of P. Banggi (cf. Enclosure III). Compact, marly limestone, beige with red patches.
Radiolaria: The small ovoid nodules of crystalline calcite which abound in the lighter parts of the rock may be attributed to internal moulds of radiolaria. The shell is no longer visible and the internal mould has been deformed by tectonic pressure.
Foraminifera (*rare*): *Nodosaria* sp., rather large species with bulbous chambers. *Chilostomella* sp.? Some sections, oval-shaped with involute chambers. *Robulus* sp., very small species. *Textularia* sp., rare. *indeterminate Foram.*, rotaloid (0·2 mm.) with coarse pores.
Period: indeterminate, Cretaceous or Tertiary (*Chilostomella* is only known from Cretaceous time onwards).

H. 7a: Ibid. Marly limestone, beige with red patches.
Radiolaria numerous in the lighter parts, elongated and compressed, usually reduced to their internal calcite mould. Shell preserved in places. Few *Nassellaridae*; *Spumellaridae* predominate.
Foraminifera very rare; the same indeterminate rotaloid foraminifera found as in H. 7.
Period: indeterminate, Cretaceous or Tertiary.

H. 50: S.Kabongi, W. coast of P. Banggi (cf. Enclosure III). Reddish-brown limestone, dark, with veins of calcite.
Radiolaria rare.
Foraminifera: a few small forms of no stratigraphical importance. *Ophthalmidiidae* and *Nonionidae*.
Period: indeterminate, Mesozoic or Tertiary.

H. 75: S.Bolayayong (Taritipan), Marudu Bay (cf. Enclosure V). Dark, reddish-brown limestone, with veins of calcite.
Radiolaria abundant, internal moulds deformed.
Foraminifera: indeterminable remains of a small specimen of the *Lagenidae* (*Lingulina* or *Glandulina*).
Period: indeterminate, Mesozoic or Tertiary.

St. 195: S.Segama, Point 69 (cf. Enclosure VIII). Blackish-grey veined limestone.
Highly altered remains of *Radiolaria*.
Period: indeterminate.

B. Globorotalia and Globigerina Limestones

H. 142, 143, 144, 147: P. Burong, NE. of P. Tiga, W. coast of B.N.B. (cf. cross-section, text Fig. 20).

H. 142, 144: Reddish limestones, partially silicified. The silicification affects principally those zones where the foraminifera have accumulated in large numbers. In this case their shells are replaced by silica.
Foraminifera: Globorotalia simulatilis Schwager.
Form variable. Some specimens resemble *Gl. aragonensis* Nuttall, others *Gl. velascoensis* (Cushman). *Globorotalia* cf. *membranacea* (Ehrenberg), rather flat species. *Globigerina* sp. abundant.
Radiolaria: a few poorly preserved specimens.
Period: probably Paleocene.
Globorotalia simulatilis is particularly widespread in the Paleocene, but is found even at the Ypresian stage. The type species come from the lower strata of the Libyan stage in Egypt.
Globorotalia velascoensis ranges from the " Velasco shales " of Mexico, which are generally attributed to the uppermost Cretaceous (Danian); but it is also found in the Paleocene.

H. 143: Light-grey limestone with traces of silicification.
Globorotalia simulatilis Schwager, specimens very closely resembling the type species.
Globigerina: numerous, of various types (*bulloides*, *tricamerata*, *velascoensis*).
One specimen of foraminifera with chambers planispirally arranged, with very short spines, resembles in that respect some species of the genus *Hantkenina*, particularly *H. lehneri* Cushman and Jarvis of the Lower Eocene of Trinidad, but differs from them in its spiral coiling, which persists even to the very last chambers. A specimen of this, partially detached by erosion, can be seen in a depression on the surface of the sample.
In the rock dust sent to us from abroad, which had been obtained by pulverizing a fragment of this sample, we found some specimens of *Globotruncana ventricosa*. White, wholly detached and easily determinable. This species belongs to the

Senonian. It is normally never found in association with *Globorotalia simulatilis*. It must therefore be assumed either that it is in a re-worked state here or that its presence was due to accidental contamination.
The writer considers this latter supposition to be the more probable. In fact, had there been any re-working, the *Globotruncana* should have suffered the same fate as the *Globorotalia* during the pulverization. They would have been found shattered or still encased in rock fragments. At any rate, none of the four thin sections of H. 143 contains any representatives of the genus *Globotruncana*.
Other foraminifera, notably an *Eponides* filled with a black sediment of extraneous origin, were present in the same pulverized sample.
Period: H. 143 is probably of Paleocene age.

H. 147: Variegated stratified limestone, silicified, with veins of calcite. Silicification particularly advanced in the zones where foraminifera had accumulated.
Microfauna similar to those of preceding samples from the same locality, but among the *Globorotalia* there are some which diverge from the simulatis type by their larger dimensions and more open umbilicus. *Globigerina* abundant.
Radiolaria: rare individual specimens in a poor state of preservation.
Period: probably Paleocene.
The microfauna of samples H. 142, 143, 144 and 147 are practically identical with those of the *Globorotalia* strata in the Apennines, described by O. Renz (Thesis, 1936). These strata belong to the Paleocene Formation, but probably began to form in Danian times, since they follow on the *Globotruncana* strata. Unfortunately we have not yet found any criteria in these fauna of small pelagian foraminifera, which would permit us to trace the boundary between Danian and Paleocene formations. The *Globorotalia* of the Borneo samples most closely resemble those of the middle and upper zones of the Apennine *Globorotalia* strata, and must therefore be attributed to the basal Tertiary rather than to the uppermost Cretaceous.

C. Globigerina Limestones without *Globorotalia*

Nh. 52: S.Bumbum, Kudat-Sequati road, Kudat Peninsula (cf. Enclosure IV).
Yellowish or light-beige limestone.
Globigerina sparse: *Globigerina conglobata* Brady. *Gyroidina* sp. rare. *Nodosaria* sp. rare.
The *Globigerina* of these beds are identical with those of the Tertiary system in Formosa, as described by Hansawa (Eoc. Foram. of Taiwan, Tôhoku Sci. Rep., 2nd Ser., Vol. XII, Pl. 29, Fig. 14, p. 616). He observed them in the black shales of the Hori Formation, whose age, in his opinion, was " pre-Miocene, in part Eocene ".
Fragment of Camerina. These minute remains are related to a form of the *Heterostegininae* group and probably to the genus *Cycloclypeus*, which has abounded in the Sunda Isles from Oligocene times until the present day.
Period: If the presence of *Cycloclypeus* is confirmed, the beds are of post-Eocene age; otherwise they can only be defined as of indeterminate Tertiary age, since the *Globigerina* and other small foraminifera present are not fossils characteristic of any particular stage.

Nh. 514: S.Tungulian, Klias Peninsula. Compact limestone, dark red, appearance of radiolarite.
Globigerina distribution very scattered, smaller and shorter than those of Nh. 52. No radiolaria.
Period: Cretaceous or Tertiary.

Summary of Estimated Ages

H. 7, 7a: Cretaceous or Tertiary.
H. 50, 75: Mesozoic or Tertiary
St. 195: indeterminate.
Nh. 142, 143, 144, 147: Paleocene to Lower Eocene.
Nh. 52: Tertiary, possibly post-Eocene.
Nh. 514: Tertiary (or Cretaceous).

APPENDIX IV

Methods of Topographical Survey

Terrestrial Survey

EVERY geological survey depends largely upon reliable topographical data. The configuration of the coastline of North Borneo was taken from the British Admiralty sea charts, which were used for the geological survey of the coastal sections. Apart from minor corrections made on the NE. coast, the coastline drawn on the maps enclosed coincides with that of the sea charts. On the other hand, as

far as the inland parts of North Borneo are concerned, few detailed official maps were at the disposal of the geological field parties. Accurate surveys have been made by the Government on the west coast and around Kudat, Sandakan, Lahad Datu and Tawau, but these surveys are not linked with each other. The greater part of the country was unsurveyed and in fact unexplored when the geological reconnaissance started; the geological field parties therefore had to make topographical surveys of their own.

In Chapter II it was shown that the geological exploration of North Borneo was carried out mainly in two periods and on behalf of two different oil companies which applied different surveying methods.

During the first regional exploration campaign, which was carried out in 1913–1915 on behalf of the *Nederlandsche Koloniale Petroleum Maatschappij*, the geologists themselves had to make the topographical survey. The western and south-eastern districts of North Borneo covered by these parties were surveyed by hand-compass and tape or pedometer. Owing to good checking by cross-connections these primitive surveys proved to be fairly reliable. The topographical sketch-maps drawn by these explorers are incorporated in the official map of the State of North Borneo (1934), scale 8 miles to 1 in.

During the second geological exploration campaign, carried out in 1935–1939 on behalf of the Royal Dutch Shell Group, the geologists had special survey parties at their disposal. The geological field parties were equipped with light mountain tachymeters; their method of survey consisted of measuring closed polygon-traverses which were connected with astro-fixed points. Some minor runs were surveyed by hand-compass and tape or range-finder.

The geological survey parties followed the rivers and streams as long as they offered rock exposures. Only in flat or undulating regions with ill-defined drainage were straight-line forest tracks surveyed. These jungle trails, of which over 500 km. were cut in Dent Peninsula alone, are not shown on the map since they are by now overgrown. Of permanent communications only the Pensiangan-Keningau bridle path and the Keningau-Melalap road were surveyed.

The following methods were used for controlling and connecting the compass traverses of the geological field parties:

(*a*) *Astro-fixes.* The geographical co-ordinates of 17 points scattered all over the country have been determined by astronomical observation. These fixed points, shown on the 1:500,000 map (Enclosure I), are listed in Table XI.

(*b*) *Theodolite and Tape Traverses.* An inland traverse was run from the Government triangulation point at Tamberledan on the eastern side of Marudu Bay to S.Tungud. A coastal traverse was also carried out around the eastern part of Dent Peninsula from Tungku to astro-fix Maruap. Intermediate solar astronomical observation stations were located at Dent Haven and Tambisan.

(*c*) *Triangulation.* Though some minor triangulation work was carried out in the coastal swamps of the Jambangan-Sugut-Labuk area and at Kuala Maruap, triangulation had to be discarded on economic and practical grounds.

Aerial Survey

In order to get an idea as rapidly as possible of general geomorphological conditions and the character of the country, it was decided to apply the aerial survey method.

The prospects being then still uncertain and, as a matter of fact, not very promising, to photograph the whole country did not seem justifiable, since this would have required the expenditure of too much time and money. Instead, reconnaissance flights over strips of the area were carried out, and in order to derive the maximum benefit from them it was decided to take aerial photographs during these flights.

The flights were carried out in 1936 and 1937 by the Koninklijke Nederlandsch-Indische Luchtvaart Maatschappij (K.N.I.L.M.) with a De Havilland Dragon Rapide and, for a short period, a Fokker VII-R. Tarakan was used as a base, being the nearest place where a landing field was available. A Zeiss RMK P 10 photogrammetric camera (focal length 10 cm.), taking a picture 18 × 18 cm., was used for the photography. The photographs were taken at an average altitude of 4,000 m. above ground level, resulting in a scale of 1:40,000. A run of "vertical" photographs on this scale covered a strip of about 7 km. in width. In order to widen the strip covered by one flight, "obliques" to the left and right and "vertical" photographs were taken alternately. The camera had a special mounting, which allowed it to be swung 23° on each side. It was arranged so as to take successively: one photograph with the axis of the camera vertical; one oblique photograph with the axis of

the camera at 23° to the vertical on the left; one similar oblique photograph to the right and another vertical one, etc. The longitudinal overlap of both the vertical and the oblique photographs was about 72%, so that in one flight a strip of ground about 17 km. wide was covered stereoscopically. The total length of the runs photographed was 1,800 km. For the purpose of this aerial survey 3,200 photographs were taken, of which 1,100 were vertical, 1,050 oblique to the left and the same number oblique to the right.

The distance from Tarakan to the farthest point covered by the strips is about 350 km.

Carrying out these photographic flights subjected the crew and equipment to a severe test, but both stood up to the work very well. Navigation was difficult owing to the fact that no reliable maps showing details of the river system or other ground features were available. Because of the unfavourable weather conditions the strips could only be covered in parts. Naturally, in a jungle-covered area like North Borneo, it was no easy navigational problem to have these parts well matched together in accordance with the projected flight lines.

When plotting the photogeological data the photogeologists also plotted the topography, e.g. rivers, etc., which could be observed from the photographs. These data had to be compiled into a map, and for this purpose it was necessary to make an aerial triangulation in order to locate the precise geographical situation of each photograph. It was not necessary to be more accurate than for normal field-geological route surveying, since the photography was considered merely as a reconnaissance survey. Consequently, it was decided to use the simplest method of triangulation, viz. graphical radial triangulation.

The ground control consisted of 11 astronomical stations, about 10 fixed points obtained by traverses which had been surveyed for the field geologists, and local triangulations. The situation of these points was identified on prints of the photographs. At some places the sea charts also were used for control along the coast. After the graphical triangulation had been concluded some more ground control became available, to which the results of the triangulation were adjusted.

Considering the precision which may be expected from the astro-fixes and the traverses, the accuracy of the identification of the points on the photographs and the closing errors of the graphical triangulation, it may be assumed that on an average the mutual error of the triangulated points is not greater than 2 mm. on the 1:500,000 map.

TABLE XI. NORTH BORNEO ASTRO-FIXES

FINAL CALCULATED VALUES

Station	Station No.	North Latitude	East Longitude	Co-ordinates in Metres referred to Government Zero at Kudat	Remarks
KUDAT	60/248	N. 6° 53′ 00·68″	E. 116° 50′ 31·50″	S. 295·54 W. 242·10	Station of origin for all values
JAMBANGAN	32/537	N. 6° 38′ 50·00″	E. 117° 29′ 08·10″	S. 26380·84 E. 70916·00	
KUALA SUGUT	55/459	N. 6° 26′ 37·80″	E. 117° 43′ 34·35″	S. 48838·24 E. 97562·30	
LAHAD DATU	59/983	N. 5° 01′ 47·28″	E. 118° 19′ 46·80″	S. 205093·40 E. 164726·60	
TUNGUD	57/702	N. 6° 03′ 11·13″	E. 117° 20′ 22·20″	S. 92104·74 E. 54825·10	End of inland theodolite traverse from Kudat
SANDAKAN	58	N. 5° 50′ 28·77″	E. 118° 06′ 51·00″	S. 115386·30 E. 140639·60	
BILIT	59/558	N. 5° 29′ 53·70″	E. 118° 12′ 20·40″	S. 153311·90 E. 150862·30	
K. MARUAP	55/421	N. 5° 25′ 31·00″	E. 118° 56′ 20·25″	S. 161147·10 E. 232149·40	
S. KRATAM	59/990	N. 5° 27′ 06·30″	E. 118° 29′ 35·70″	S. 158370·84 E. 182744·60	
KG. KUAMUT	60/267	N. 5° 13′ 28·30″	E. 117° 29′ 40·80″	S. 183711·34 E. 72105·70	
TANKULAP	57/447	N. 5° 18′ 18·71″	E. 117° 17′ 05·10″	S. 174808·60 E. 48827·30	Kinabatangan River fixes
PINANGA	60/64	N. 5° 12′ 34·10″	E. 116° 49′ 54·30″	S. 185412·80 W. 1387·80	
LAMAG	55/690	N. 5° 28′ 37·11″	E. 117° 49′ 08·40″	S. 155735·10 E. 108023·00	
SEBATIK IS.	54/355	N. 4° 13′ 50·75″	E. 117° 38′ 12·00″	S. 293589·00 E. 87980·10	Starting point for air survey
KENINGAU	59/548	N. 5° 20′ 32·30″	E. 116° 09′ 33·45″	S. 170684·60 W. 75922·80	Geol. traverse closing error = 300 m.
PENSIANGAN	P	N. 4° 32′ 26·86″	E. 116° 18′ 45·50″	S. 259332·50 W. 58997·70	Geol. traverse closing error = 400 m.
BELURAN	59/907	N. 5° 53′ 49·76″	E. 117° 33′ 14·26″	S. 109319·80 E. 78589·60	By triangulation from Sandakan Station, 58
LAWAS	C.M. 5/610	N. 4° 51′ 37·66″	E. 115° 23′ 57·25″	S. 223834·02 W. 160290·58	From Sarawak Govt. records
DENT HAVEN	76	N. 5° 16′ 05·49″	E. 119° 14′ 40·63″	S. 178406·74 E. 266092·12	By traverse from Maruap Station
KAMABONG		N. 4° 54′ 40·94″	E. 115° 55′ 28·31″	S. 218305·54 W. 102014·40	From B.N.B. Govt. records. Not observed. Approx. only.

Locality Index

(The figures 5/116, etc., after the place name indicate the latitude and longitude of the south-west corner of the degree square in which the place occurs.)

Babagkang River	5/118	32
Bagahunan Hill	5/116	8
Bakungan Islands	6/116	23, 31
Balambangan Island	7/116	1, 5, 11, 15, 21, 22, 64, 73, 74, 95
Bangan River	5/117	27, 30
Bangau Headland	6/116	74, 75, 87
Banggi Island	7/117	1, 5, 12, 14, 15, 19, 20, 21, 22, 30, 64, 65, 74, 87, 89, 91, 95, 98, 99
Baram River	3–4/114–5	4
Batawan Island	7/117	65
Batu Larei Larei Headland	6/118	64
Batu Lugas	6/116	51
Batu Matindok	6/116	76, 77
Batu Penotal	5/115	10
Batu Punggul	4/116	98
Batu Puteh	5/117	21
Batu Selawak	5/118	20
Batu Tapadong	5/117	21, 30, 95
Batu Tatak River	5/118	76, 77
Batu Timbang	5/117	8
Batu Tulis	5/117	8
Batu Tumanggong	5/118	6
Bawain River	6/116	59
Bayudon River	4/117	9
Beaufort	5/115	2
Bedakson Hill	5/118	32
Bengkoka Peninsula	6/117	1, 9, 11, 13, 14, 20, 29, 30, 75, 91, 95
Berhala Island	5/118	20, 41, 106
Besalag Nemud	5/118	24
Biag Tagai River	5/118	32
Blantian River	4/117	2, 5, 11, 12, 67, 68, 69, 70, 71, 73, 75, 77, 92, 96, 103, 104, 105
Boaan Island	6/118	23, 24, 31
Bol	4/115	29
Bole River	4–5/117	67, 90
Bongaya River	6/117	30
Bongon River	6/116	89
Brunei	4–5/115	4
Brunei Bay	4–5/115	1, 2, 5
Burong Island	5/115	65, 94
Celebes Sea		1, 2, 15, 22, 31
China Sea (South)		1, 2, 9, 15, 30, 47
Connor Mountain	4/118	38
Cowie Harbour	4/117	1, 11, 104
Crocker Range	5–6/116	1, 2, 9, 11, 26, 47
Dadong Besar River	4/118	101
Dadong Kechil River	4/118	101, 102
Darvel Bay	4/118	1, 5, 12, 15, 16 30, 33, 64, 71, 90, 91, 95, 96, 98, 100, 101, 105
Dent Peninsula	5/118–9	1, 5, 6, 7, 11, 12, 14, 15, 18, 19, 20, 21, 22, 23, 24, 27, 31, 32, 33, 34, 35, 37, 38, 41, 64, 73, 106
Dewhurst Bay	5/118	11, 20
Diwata River	4/118	16, 71, 90, 98
Gaya Bay	6/116	11
Gaya Island	4/118	31, 32
Gaya Island	6/116	26
Giram Besar River	4/117	10
Gomantong Hill	5/118	21
Gumgum River	5/117	41
Imbok River	5/117	71, 96
Jesselton	5/116	2, 26
Kadamayan River	6/116	49, 50, 76, 77, 90
Kalabakang River	4/117	2, 5, 7, 9, 11, 20, 21, 26, 27, 92, 97
Kalibangan River	5/116	94
Kamabong	4/115	9
Kamburanga	6/116	57
Karamuak River	5/117	8, 71, 78, 90, 96, 100
Karang River	5/117	90, 96
Kargan Mountain	6/116	59
Kimanis Bay	5/115	1
Keningau	5/116	2, 5, 6, 9, 26, 97
Keningau Plain	5/116	11
Kinabalu Mountain	6/116	1, 2, 4, 5, 6, 7, 9, 12, 14, 15, 21, 26, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 67, 71, 76, 77, 83, 90, 91, 97, 106
Kinabatangan River	5/116–8	1, 2, 4, 5, 6, 7, 8, 9, 10, 12, 13, 20, 21, 22, 23, 26, 27, 28, 29, 30, 31, 64, 70, 71, 75, 78, 85, 90, 91, 96, 100
Kiniau Hill	5/116	8
Klias Peninsula	5/115	1, 4, 6, 10, 15, 16, 20, 21, 22, 24, 25, 65, 94
Klumpang Island	4/118	38

Klumpang River	4/117–8	2, 5, 32, 33, 39, 41
Kota Belud	6/116	25, 65, 67, 77, 88, 89
Kratam River	5/118	20
Kuamut	5/117	22, 27, 30
Kuamut River	4–5/117	2, 7, 8, 9, 20, 21, 30, 70, 71, 75, 91, 96, 100
Kudat	6/116	2, 20, 99, 100
Kudat Bay	6/116	100
Kudat Harbour	6/116	72, 82, 85, 95, 100
Kudat Peninsula	6/116–7	1, 4, 6, 12, 14, 15, 16, 19, 20, 24, 27, 29, 51, 59, 65, 74, 87, 91, 94, 95, 98, 99, 105
Kulapis River	5/117	20
Labau River	4–5/116	1, 2, 8
Labong	6/116	49
Labuan	5/115	4
Labuk Bay	6/117	1, 21, 27
Labuk River	5/116/7	1, 2, 4, 5, 8, 15, 19, 20, 30, 57, 94, 106
Lagungan River	4/116	7, 9
Lahad Datu	5/118	2, 6, 12, 68, 69, 90, 101
Lakutan River	5/115	11
Lamag	5/117	21
Langaan Island	6/118	23, 31
Langanan River	6/116	50
Langkom	6/116	25
Lawas	4/115	29
Liheiman Island	6/118	23, 24, 31, 134
Limbuak River	7/117	99
Liwagu Kuananan River	5–6/116	8
Liwagu River	5–6/116	49, 57
Lohan River	5/116	8
Lokan River	5/117	20
Lokpadsang Headland	6/116	27
Loro Headland	6/116	51
Luis River	4/117	10
Lumbidan	5/115	24
Madai Mountain	4/118	95
Madai River	4/118	101
Magdalena Mountain	4/117	9, 32
Makadau River	6/116	50, 67, 91, 97
Malog River	5/117	70, 71
Malua River	5/117	9, 27, 30, 75, 85, 100
Mamut River	6/116	50
Manawali Island	7/117	1, 12, 14, 64, 68, 89, 99
Mangalum Island	6/115	6, 7, 15, 16, 22, 24, 25
Mantanani Island	6/116	24
Mantaranau River	6/116	51
Marudu Bay	6/116	1, 4, 11, 25, 64, 74, 89, 90
Marutai River	4/117	12
Masmas River	4/117	12, 104
Melalap	5/116	2
Mengalong River	5/115	11
Mensian River	5/115	4
Mensuli River	5/118	33, 83
Mentapok Mountains	5/117	8
Merali River	6/116	8, 51, 59
Meriangin Besar Island	7/117	98
Milian River	5/116	8, 9, 12, 13, 20, 21, 27, 51, 59, 64, 78, 90, 91, 96, 100
Miri River	4/113	4
Mungkuou River	5/118	32, 38, 41, 102
Ngklanjau River	4/117	10
Nosong Headland	5/115	24
Nosong Shoals	5/115	24
Nunuyan Island	5/118	23, 31
Oisapad Hill	6/116	58
Padas Bay	5/115	4
Padas Gorge	5/115	10
Padas River	4–5/115	1, 2, 8, 9, 10, 11, 26, 97, 106
Paitan Bay	6/117	1
Paitan River	6/117	24
Paka Cave	6/116	49, 50, 57
Pakat River	5/118	41
Paninsau River	4/117	67, 104
Paranchangan	6/116	5, 58, 59, 67, 89
Pau Hill	5/116	8
Pegalan River	5/115–6	1, 2, 10, 26
Penataran River	6/116	47
Penawan River	4/116	2
Pensiangan	4/116	6, 9, 97
Pinanga	5/116	5, 6, 8, 9
Pinanga River	4–5/116	4, 5, 21, 27
Pingan-Pingan	6/116	90
Pintasan	5/117	27
Prapat Headland	5/118	34
Pungulupi River	5/118	12, 102
Ranau	5/116	10, 49
Ranau Plain	5/116	1, 11
Rara Mountain	5/117	8, 9, 27, 51, 59
Rashleigh River	5/118	32, 38
Rindian Hill	6/116	88
Ruby Island	7/117	87
Sakar Island	4/118	12, 98, 101
Sandakan	5/118	1, 2, 4, 5, 7, 20, 23, 31, 34, 41, 64, 106
Sandakan Bay	5/117–8	1, 5, 10
Sandakan Harbour	5/117–8	10, 106
Sandakan Peninsula	5/117–8	1, 4, 6, 23, 33, 34, 41, 106
Sangitan River	5/117	85, 100
Sapagaya River	5/118	101
Sapa Puti Rasang River	5/118	23
Sapulut	4/116	6, 97
Sarudong River	4/117	2, 5, 9, 10, 11, 21, 26, 27, 30, 92
Sebahat River	5/118–9	32
Sebatik Island	4/117	6, 15, 16, 24, 31
Sedalir River	4/116	5
Segama River	4–5/117–8	2, 4, 5, 6, 7, 9, 10, 12, 15, 16, 19, 20, 21, 23, 30, 31, 32, 33, 34, 41, 47, 65, 67, 71, 72, 76, 77, 83, 89, 90, 91, 92, 95, 96, 100, 101, 104, 105, 106

Sembakong River	4/116	2, 7, 9, 12, 13, 97, 98
Sepulot River	4/116	2, 9, 20, 21, 98
Sequati	6/116	6, 15, 24
Sequati River	6/116	16
Sibuda River	4/116	2, 5, 7, 20
Sibumbung Estuary	7/117	99
Sidongal Headland	4/118	37
Sigalong Hill	4/118	39
Siglayan River	4/117	10
Silibukan River	5/118	32, 41, 101
Silimpopon	4/117	27
Silingaan Island	6/118	23, 31
Simengaris River	4/117	31
Simporna	4/118	5
Simporna Peninsula	4/118	1, 5, 11, 14, 20, 24, 25, 27, 31, 32, 33, 35, 37, 38, 39, 41, 51, 75, 82, 106
Sinoa River	5/117	9, 51, 59, 96
Sirar Headland	6/116	42, 51, 59
Sirar Island	6/116	51, 59
Subahan River	4/118	16, 33, 41, 69, 71, 90, 101
Sugut River	6/116–7	1, 2, 4, 5, 8, 50, 51, 58, 59, 67, 89, 91, 97
Suk Plain	5/116	11
Suk River	5/116	1, 2, 5, 8, 10
Sulu Sea		1, 2, 9, 15, 20, 22, 24, 30, 31, 47
Tabakau	5/117	21
Tabanak River	5/118	32, 34, 41, 90
Tabin River	5/118	23, 31, 41
Tadul	6/116	59
Ta Island	5/117	76, 77
Tagai	5/117	22
Talangkai River	4/116	2, 6, 20
Talaud Islands		82, 83, 84
Tambalunan River	4/117	9, 10, 11, 27
Tambuku Mountain	4/117	12, 92, 104, 105
Tambunan	5/116	10, 26
Tambunan Plain	5/116	1, 11
Tampasuk	6/116	25, 30
Tampasuk Hill	6/116	77
Tampasuk River	6/116	49, 90
Tampias	5/117	94
Tangkulap	5/117	8, 9, 21, 27
Tanna Island	4/118	101
Taritipan River	6/116	65
Tawau	4/117	2, 5, 7, 32, 33
Tawau River	4/117	32, 37, 39
Telewas River	5/118	12, 83, 90, 100, 101
Tenom	5/115	2, 5, 9, 10, 11, 97
Tenom Plain	5/115	11
Tiagau River	4/117	7, 9, 20, 97
Tiga Island	5/115	24
Timbun Mata Island	4/118	31, 37
Tingkayu River	4/118	12, 65, 96, 101
Tinompok	6/116	50
Togopi River	5/119	7
Trusmadi Mountain	5/116	2, 5, 26, 97
(Tuaran) Toaran	6/116	25, 59
Tuaran River	6/116	25, 26, 51
Tulit River	4/116	98
Tungku	5/118	7, 24, 33, 37, 40, 102
Tungku River	5/118	12, 21, 23, 31, 32, 34, 37, 38, 41, 73, 102
Tungud River	5–6/117	8
Wariu River	6/116	88
Weston	5/115	11

General Index

Actinolite, 67, 68, 91, 100, 103, 104
Actinolite-clinozoisite-schist, 101
Actinolite-muscovite-schist, 100
Adamellite, 52
Adinole, 77
—— formation, 85
Adinole-schist, 88
Admiralty charts, 148
Aerial photographs, showing changes in river courses, 105
—— synclinal basins revealed by, 27
—— used for tracing mud volcanoes, 23
Aerial survey, 149, 150
—— triangulation, 150
Albite, 50, 98
Albite-gabbro, 71
Albite-diabase, 74, 80
Amphibolite, 99, 100, 103, 104
—— in Danau formation, 63, 92
Amygdaloidal diabase, 74
Amygdaloidal structure of spilites, 75
Analcite-diabase, 73, 74, 79, 81
Andesine, 35, 37
Andesite, 51
—— dykes, 32
Andesite-basalt, 35
Andesitoids, 37
Anglo-Persian Oil Company, 6
Anglo-Saxon Petroleum Co., Ltd., xi
Anorthite, 35
—— content, classification by, 37
—— method of determination of, in phenocrysts, 35
Anthozoa, 5
Aplite, 52
Arcuate extinction of augite, 74, 75, 78
Arkose, 98
Arsenopyrite, 90
Astro-fixes, 149
Augite, 73
—— arcuate extinction, 74
—— in Mt. Kinabalu minor intrusions, 58
—— occurrence in Tertiary Volcanic rocks, 42

Bächlin, R., 7, 27, 97, 98
Bandaite, 43
Bangan synclinal basin, 27
Barytes, in calcified cherts, 86
—— in ophicalcites, 87
—— in radiolarian cherts, 65
Basalt, 72, 74, 80, 81
—— sills or lava flows, 95
Basel Museum of Natural History, specimens, maps, reports, lodged at, 5
Basement rocks, 11
Bastite, 67, 68
Bataafsche Petroleum Maatschappij, xi, xiii, xiv
Bearth, P, 41, 46, 47, 59
Bemmelen, R. W. Van, 85
Bernoulli, W., 4
Beskow, G., 93
Biotite-hornblende-andesite, 35
Biotite-hornblende-dacite, 35, 37
—— lapilli of, 40
Birang Formation, 18, 21
Bird's-nest, edible, caves, 8, 21
Blumenthal, M., 6
Bongaya Formation, 16, 21
Bongaya syncline, 27
Borloz, A., 5, 37
Boissevain, H., xiii, 10
Bowen, N. L., 46, 79
Bowlingite, 69, 71, 75, 87
Breunnerite, 87
Brine springs, 22, 23
British Borneo Exploration Company, 4
British Borneo Petroleum Syndicate Ltd., 4
British North Borneo Company, xi, xiv, 3, 90
Bronzitite, 68
Brouwer, H. A., 29, 30
Brucite, in serpentine, 67
Bruggen, G. Ter., 98
Bücking, H., 5
Burri, C., 42, 63, 78, 79, 84, 85
Bytownite, 35
—— andesite, 37

Calamites, 96
Calc-alkali type of magma, 62, 85
Calcified breccia-tuff, 87
Calcified diabase, 87
Calcified gabbro, 87
Calcified serpentine, 86
Calcite in basalt, 75
—— in diabase, 73
—— in metasomatized ophiolites, 86–88
—— in metasomatized sediments, 88
—— in mud volcanoes, 23
—— in ophiolitic breccias and tuffs, 77, 78
—— in radiolarian cherts, 65
—— in serpentine, 67
—— in silico-carbonate rocks, 86
—— in slate formation, 97, 98
—— in spilites, 75, 76
—— in spilite breccias, 50
Carinthine-eclogite, 102
Carinthine hornblende, 102
Caves, edible bird's-nest, 8
Celadonite, 40
Cenomanian, 96
Central-East Borneo Expedition, 1925, 96
Chalcedony in ophiolitic breccias, 77
—— in radiolarian cherts, 65
—— in spilites, 75
Chalcedonite, 85
Chalcopyrite, 90
Chert, 97
Chert, calcified, 86
Chlorite, 50, 52, 67, 73, 75, 77, 78, 87, 98
Chlorite-albite schist, 99
Chlorite-serpentine, 40
Chrome iron ore, 89
Chromite, 16, 86, 87, 89
—— placers, 89
Clay-slate, 97
Climate, 2
Clino-zoisite, 67, 77, 101, 103, 104
Coastline physiography, 1, 11

Columnar structure, in andesite, 51, 59
Conglomerates, basal, of Eocene, 19, 98
—— in slate formation, 97
Conglomeratic breccia, 78
Copper mine, abandoned, 71
—— on Karang River, 96
Coral reefs, 11
Cox, L. R., 7, 22
Crocidolite, 98
Crypto-dacite, 37
Crystalline schists, 11, 12, 98, 99, 105
—— in mud-volcanoes, 23
—— occurrences of, 99–104
—— their age, 12, 99

Dacite, 35
Dacite-Andesite-Basalt Series, 33, 35
Danau Formation, 12, 13, 23, 24, 30, 41, 48, 50, 62, 63–97, 102, 105
—— definition, 63, 64
—— in Dutch Borneo, 96
—— isoclinal folds in, 91
—— its age, 13, 94–97
—— occurrence, 64
D'Arcy Exploration Company, 6
Darvel Bay strata, 65
Davis, E. F., 93
Deer, W. A., 56
Delessite, 75
Devonian, 96
Dewey, H., 78, 81, 93
Diabase, 63, 72, 73, 74, 81
—— calcified, 87
—— porphyrite, 73
Dieseldorff, A., 89
Diopside, 68
—— bearing rock, 57, 58
Diorite, 100
Discocyclina, 138
Dolerite, sills or lava flows, 95
Dolomite, 86
Drainage system, 8
Drilling, 4, 6, 7
Dufour, J. xiii
Dunite, 50, 68, 79, 89, 91
Dunite-serpentine, 67
Dynamic metamorphism, 97

Edenite, 103
Ellis, E., 37
Eocene, basal conglgomerates, 19
—— conditions of land and sea, 19, 20
—— limestone, 30
Epidote, 52, 67, 72, 73, 78, 87, 99
Epidote-chlorite schist, 100
Epidote-hornblende schist, 99
Es, L. J. C. van, 29
Esenwein, P., 68, 69, 70, 79, 81
Eskola, P., 92
Exploration, 3
—— in the Segama River, 4
Extrusive rocks of Ophiolite Series, 72–85

Felix, J., 5
Flett, J. S., 78, 81, 93
Flysch, lack of fossils in, 65
—— sandstones, 64
Folding, Tertiary, 25–27
Foraminifera in matrix of tuffites, 40
—— in metamorphosed sandstone, 51
Foraminifera in pyroclastic rocks, 33
—— in " squeezed strata ", 65
—— larger, in Tertiary rocks, 17, 18, 21, 137–146
—— smaller, in Tertiary rocks, 18, 19, 21
—— used to determine stratigraphical succession, 105, 106
Frenzel, A, 56
Fusulinidae, 96

Gabbro, 99
Gabbro, calcified, 87
—— in Danau formation, 63, 68, 81, 96
Gabbro-diabase, 72
Gabbro-breccia, 77
Ganduman Formation, 18
Garnet, 59, 68, 100, 102
—— in Mt. Kinabalu minor intrusions, 58
Garnet-bearing rhyodacite, 60
Garnet-gneiss, 102
Gas-seepages, 15, 22–24
Geomorphology, 7
Geosyncline, not formed in North Borneo, 94
Gerth, H., 5
Gilluly, J., 93
Glauconite, 40
Glaucophane-schist, 63
Glass, J. J., 89
Glauser, E., xiii
Globigerina, 93
Globigerina limestones, 94, 147, 148
Globigerina marls, 93, 96
Globorotalia, 94, 95
Globorotalia limestone, 95, 147, 148
Globorotalian marl, 96
Gneiss, 100
—— injection, 100
Gold, 16
—— in chromite placer deposits, 89
—— in quartz vein, 90
—— origin of, 90, 105
—— placer, 90
Gold prospecting, 4, 10
Gomantong limestone, 21
Gonyer, F. A., 56
Granitization, 49
Granodiorite, 52, 58
—— in Tertiary Strata at G. Rara, 9
Greywacke, 96, 97, 98
Grits, 97
Grütter, Dr., xiii, 69, 89

Halobia, 96
Hartmann, E., 5
Harzburgite, 50, 68
—— serpentine, 67
Hatton, Frank, 4, 89
Heim, A., 24
Hinde, G. J., 65, 96
Hocart, R., 5
Homma, F., 37
Hornblende in Mt. Kinabalu plutonics, 54–58
—— magnetic, 61
Hornblende-gneiss, 101
Hornblende-hypersthene-andesite, 35
Hornblende-plagiocase-schist, 101
Hornfels, 50, 96, 100
Hotz, W., xi, xiv, 5, 6, 25, 47, 50, 64, 65, 68, 89, 91, 92, 94, 95, 97, 98
Hypersthene in Mt. Kinabalu minor intrusions, 58
—— occurrence in Tertiary volcanic rocks, 42
Hypersthene-andesite, 38, 42

Ice, mechanical disintegration by, 50
Imbricate structure, in Danau Formation, 91, 95
—— in Slate Formation, 97
—— small-scale, 25
Inarad anticline, 27
Inesite, 89
Inhabitants, 3
Injection-gneiss, 100
Iodine in salt springs, 22
Irving, J., 6, 43, 56, 65

Jadeite, 67, 91
Jadeitite, 67
Jezler, H., xiii, 5, 6, 76, 91, 92, 101
Jongh, W. D. Munniks de, 5, 97
Jurassic, 96

Kalabakang formation, 97
—— shales, 20, 106
Kapilit sandstone, 10
Keratophyre, 76, 77, 80, 81, 84
Keunen, Ph. H., 30
Koninklijke Nederlandsch-Indische Luchtvaart Maatschappij, 149
Koolhoven, W. C. B., 85
Krokström, T., 35
Kuhara Mining Company, 6
Kulapis Formation, 16
Kunitz, W., 56

Labradorite, in phenocrysts in Tertiary volcanic rocks, 35
—— andesite, 37
Laccolith, porphyry, 51
Lacustrine beds, 9, 10, 11
Larsen, E. S., 43, 56
Laterite, 70
—— iron-rich, 89
Lava-streams, 32
Leicester, P., xiii, 6, 7, 68, 101
Lepidocyclina, 95, 138
Leucoxene, 87
Leupold, W., 137
Lherzolite, 68
Lignite, 16
—— blocks in volcanic conglomerates, 32
Limestone, black, 65, 96
—— Danau Formation, 65, 66, 94
—— Eocene, 98
—— in ophiolitic breccia, 78
—— Miocene, 95
—— radiolarian, 147
—— siliceous, 86
—— silicified, 86
—— Tertiary, 95
Limonite, pisolitic, 89
Limonitized spilite, 89
Lotti, B., 63, 93

Magma type, calc-alkali, 62
Magma type, Pacific, 33, 43, 62
Malua synclinal basin, 27
Manganese mine, Marudu Bay, 65, 89
—— ore, Marudu, 16, 89
—— ore, Marudu Bay, 4, 89
Marchet, A., 56
Marls, *globigerina*, 93, 96
—— of Danau Formation, 65, 96
Maruap Formation, 18
Mediterranean orogenesis, 78
Mensuli Limestones, 34
Meladiorite, 103
Metasomatized sediments, of Danau Formation, 88
Metasomatites, quartz-carbonate, 86
Methane, from mud-volcanoes, 23, 24
Microgranitic rocks, 57
Micro-granodiorite, 51, 59
—— dyke, 91
Micro-tonalite, 46
Miharaite, 38, 39, 41, 43, 47
Minor Intrusions and Extrusions, of Mt. Kinabalu, 50, 58
Miocene, 22
Mohler, W., 35
Molengraaff, G. A. F., 30, 63, 65, 85, 90, 93, 96, 97
Monomict breccia, 77, 78, 90
Monotis, 96
Monsoon, south-west, 3
Mountains, formed of Tertiary igneous rocks, 9
—— relation to drainage system, 8
Mt. Kinabalu massif, 47, 63
—— age of, 62
Mud-volcanoes, 15, 22–24
—— calcite and pyrite crystals in mud, 23
—— in Moluccas, 24
—— methane from, 23
—— solfataric activity, absence of, 24
—— traced from aerial photographs, 23
Mylonite, 68

Nappe structures, 92
Natrolite, 75
Nederlandsche Koloniale Petroleum Maatschappij, xi, xii, 6, 137, 149
Neogene, folding in, 27
—— volcanism, 24
Nephrite, 67, 91
Niethammer, G., xiv, 4, 5, 6, 25, 47, 50, 51, 59, 64, 65, 67, 68, 75, 81, 88, 91, 93, 94, 95, 97, 98
Niggli, P., 37, 42, 63, 78, 79, 81, 84, 85
Niggli molecular norm, 55
Nockolds, S. R., 56
Norite in Danau Formation, 63
Nummulites, 96

Oil Prospecting, 4, 5, 6
Oil seepages, 4, 15, 16, 22, 24
Old Slate Formation, Dutch Borneo, 98
Olivine, 35, 67, 68, 70, 71, 91
Olivine-basalt, 39, 41, 45, 47
Olivine-gabbro, 67, 69, 71, 79
Omphacite, 102
Opal, in spilites, 75
Ophicalcite, 86
Ophiolites, 12, 13, 16, 47, 48, 50, 58, 62–67, 72, 75, 77, 78–88, 92–100, 102, 105
—— associated with mountain chains, 78
—— connected with ore-mineralization, 89, 90
—— in Slate Formation, 97
—— metamorphic, 90, 91
—— metasomatized, 86
—— nature of mineral content, 78, 79
—— their petrochemical characteristics, 79
Ophiolite-breccia, 72, 77
Ophiolite-tuff, 72, 77
Ore-bearing sandstone, 51
Ore-minerals, 16
Ore-mineralization, in Danau Formation, 89, 90
Oscillatory zoning, in plagioclase, 36, 37, 41, 52, 53
—— in potash-soda feldspar, 54

" Oude Leiformatie ", Dutch Borneo, 98
Overeem, M. J. A. van, 81
Overthrusts, in Danau Formation, 92

Pacific type of magma, 33, 43, 62
Palaeogeography, 19–22
Pantanelli, D., 63
Pantellerite, 82
Parsons, H., 7
Pecopteris, 96
Pellatispira, 138
Peneplains, 1, 2, 9
Pennine, 87
Peridotite, 48, 50, 91
—— in Danau Formation, 66, 68, 77, 81
Permo-Carboniferous, in Dutch Borneo, 96
Phemister, J., 53
Phenocrysts in Tertiary volcanic rocks, 35
—— mineralogical composition, 35, 36
—— specific gravity, 36
Phyllite, 97
Physiography of North Borneo, 1, 16
Picotite, 87
Pigeonite, 39, 42
Pigeonite-augite, 39, 42, 47, 75
Pillow-lavas, 63, 75, 85
Pilz, R., 4, 89, 90
Pisolitic limonite, 89
Placer chromite, 89
Placer gold, 90
Plagioclase-hornblende-gneiss, 103
Plains, Tertiary erosion, 9
—— alluvial, lacustrine, 9
Platinum, 89
Pleistocene, 22
Pliocene, 22
Plutonic rocks, of Mt. Kinabalu, 47, 48
—— relation to morphology, 47, 49
Polymict breccia, 77, 78
Posewitz, Th., 3, 90
Prehnite, 50, 52, 68, 70–73, 77, 87, 88, 104
Preiswerk, H., 69, 79, 80
Prospecting for Oil, 4–7
Psilomelane, 89
Pyrite, copper-bearing, 90
—— crystals in mud-volcanoes, 23
Pyroxene-andesite, 35, 41
Pyroxene-basalt, 35
Pyroxene-dacite, 35
—— lapilli of, 40
Pyroxenite, 68
Pyrrhotite, 90
Pumpellyite, 73, 75
Pyrolusite, 89

Quartz, crystals, 52, 97
—— in diabase, 73
—— in metasomatites, 86
Quartz-carbonate metasomatite, 86
Quartz-diorite, 72 79, 81, 83, 100, 105
—— of Mt. Kinabalu, 58
Quartzite, 97
Quartz-monzonite of Mt. Kinabalu, 47–58, 90, 91

Radiolaria, 93
Radiolaria, badly preserved in cherts, 65
Radiolarian cherts, limestone, 147
—— manganese in, 89, 90
—— of Danau Formation, 63–65, 67, 77, 85, 86, 91, 92, 94, 95, 99, 102, 104
Raised beaches, 11
Reef-facies, 30
—— throughout Tertiary on Banggi and Balambangan Islands, 22
Reichel, M., xiii, 6, 65, 66, 94
Reinhard, M., ix, xi, xiii, xiv, 5, 6, 10, 19, 20, 32, 35, 50, 64, 70, 75, 92, 93, 96, 103
Reworked Eocene foraminifera in Te-f beds, 17, 20
Reworked foraminifera, 138
Reworked pre-Tertiary, 20
Rheden, Pannekoek van, xiii, 4–6
Rhyolite, 76, 77
Rittmann, A., 33, 35
River capture, 10
Rivers, 2
—— their watersheds, 8
Roever, W. P. de, 64, 73, 75
Roofing, slates, 97
Roothaan, J. Ph., 6, 64, 81, 82, 84, 91, 96, 100
Royal Dutch/Shell Group, xiii, xiv, 6, 7, 149
Rutile, 101, 102, 103
Rutten, L. M. R., 5, 51, 95, 137
Rutten, M. G., 6, 96, 98, 138
Rutter, Owen, 3, 89

Sakalawite, 43
Salinity of salt springs, 22
Salite, 103
Salite-edenite-hornfels, 103
Salt-water springs, 22, 24
—— constituent salts, 22
—— iodine, 22
—— salinity, 22
Salt licks, 22, 23
Santul Formation, 18
Sarawak Oilfields, Ltd., xi
Saussurite, 66, 67, 71, 104
Saussurite-gabbro, 71
Schaller, W. T., 89
Schalstein, definition, 87
Schmidt, C., 4, 24
Schneeberger, W. F., xiv, 6, 7, 27, 30, 91, 95, 97, 98
Schumacher, P. von, 7
Schürmann, H. M. E., ix, xi, xiv
Sebahat Formation, 18, 19, 34
Sembakong Formation, 97
Sericite, 98
Serpentine (mineral), 50, 68
Serpentine (rock), 99, 104
—— in Danau Formation, 63, 66, 67, 81, 86, 91, 92
—— in Slate Formation, 98
Shale, 97
Shell Company of British North Borneo Ltd., xi, xii, 6, 137
Sill porphyry, 51
Sills (or lava flows), 95
Simengaris Formation, 18
Skarn, 96
Skertchley, S. B. J., 90
Slate Formation, 12, 20, 50, 97, 98, 105
—— its age, 12, 13, 98
—— unfossiliferous, 98
Slates, roofing, 97
Slumping, 92
Soil, 7, 106
Solfataric activity, absence of, in mud-volcanoes, 24
Spaenhauer, F., 35
Spiegelhalter, F., xiii, 5, 6, 32
Spilite, 63, 64, 72, 75, 77, 80, 81, 92
—— limonitized, 89
Spilite-breccias, 50
Spilitic suite, 78

Spilosite, 88
Spinel, 68, 69, 71, 86, 103
" Squeezed strata ", in foraminifera in 65, 83, 94
—— in Danau Formation, 64, 65
Stamm, K., xiii, 5, 6, 21, 32, 34, 64, 65, 67, 75, 76, 90, 91, 92, 101
Staub, R., 29
Steiger, J. von, 46, 47, 56, 74, 79, 80, 81, 88, 100
Steinmann, G., 63, 78, 93
Stigand, I. A., 4, 11
Stocks, basalt, 96
Stratigraphical correlation, 16, 17
Sulphide ores, 90
" Summit plateau " of Mt. Kinabalu, 47, 48
Sung, G., 7
Supu limestone-breccia, 21
Survey, aerial, 149, 150
—— topographical, 148–150
—— terrestial, 148, 149
Synclinal basins, 27
—— revealed by aerial photography, 27

Tabanak beds, 34
Tagai (mud-volcanoes), 22, 23
—— traced from aerial photographs, 23
—— (salt licks), 22, 23
Talc, in peridotites, 68
—— in serpentine, 67
—— in slate formation, 98
Talc and chlorite rock, 67
Teall, J. J. H., 63
Telassau Formation, marine, 18
Tertiary beds, distribution and general description,
a-b, 19
e_1-$_4$, 20
e_5-f, 21
Pliocene and Pleistocene, 22
Tertiary conditions of land and sea, 19–22
Tertiary earth movements, 14, 15
Tertiary erosion plains, 9
Tertiary folding, 25–27
a-e_4, 27
e_5-f, 27
Tertiary Formation subdivision, 14
—— letter classification, 17
—— lithological correlations, 16
Tertiary igneous rocks form mountains, 9
Tertiary orogeny, 21
Tertiary sediments and Tectonics, 16
—— stratigraphical and subdivision compared with European, 17, 19–22
—— unconformities, 16, 17
Tertiary tectonics, 25–29
—— major features, 29–31
—— trend lines, 30
Tertiary Volcanic rocks, 31–35
—— chemical composition, 41
—— geographical position, 31
—— mode of occurrence, 31–33
—— nature of volcanic activity, 31–33
—— petrology, 35–47
—— phenocrysts in, 35
—— San Juan, California, 43
—— tuff-tuffite series, 39–41
Tertiary volcanism, 14, 15
—— age of, 33–35
—— explosive nature of, 32
—— of Pacific type, 33
Theodolite traverse, 149
Tobler, A., xiv
Tonalite, of Mt. Kinabalu, 38
Togopi Formation, 16, 18, 22
Topography of North Borneo, 1, 7
—— its relation to geology, 9
Topographical survey, 148, 150
Triangulation, 149
—— aerial, 150
Triassic, in Dutch Borneo, 96
Tridymite, in andesites, 35, 37
Troctolite, 66, 69, 70, 79, 87
Tuff, 39–41
—— definition, 39
Tuff-breccia, 39–41
—— definition, 39
Tuffite, 39–41
—— definition, 39
Tuffite-breccia, 39–41
—— definition, 39
Tuffite-limestone, 78
Tungku beds, 34
Tungku conglomerate, 23
Tungku Formation, 16
Tungku metamorphic rocks, 102, 103
Twinning, in plagioclase, 52, 69, 73
—— in plagioclase of crystalline schists, 104
—— in potash-soda feldspar, 54

Ubachs, J. G. H., 98
Umbgrove, J. H. F., 17, 30, 137
Uralite, 71, 73, 91, 104
Uralite-gabbro, 69

Variolitic spilite, 75
Verbeek, R. D. M., 56
Vlerk, I. M. van der, 6, 17, 18, 33, 37
Vögtli, W., 41, 47, 72, 74, 79, 80, 81, 100
Volcanic agglomerate, definition, 39
Volcanic breccia, definition, 39
Volcanic conglomerate, definition, 39
Volcanic activity in Te times, 20

Wad, 89
Wahl, K, xiii
Wanner, J., 5, 6, 19, 21, 32, 34, 65, 67, 90, 92, 96, 101
Watersheds, 8, 16
Weathering, of Kinabalu plutonic rocks, 49
Weber, F., 24
Wehrlite-serpentine, 86
Wenk E., ix, xi, xiii, xiv, 6, 7, 35, 43, 46–48, 50, 51, 55, 70, 85, 90, 91, 96–98, 100, 102
Wentworth, C. K., 39
Willems, H. W. V., 41
Williams, H., 39
Window, 97
Witkamp, 96
Worth, W. J., 3, 90

Yabe, H., Palaeontological examination by, 6

Zeijlmans, van Emmichoven, C. P. A., 85, 96, 98
Zeolite, 75, 77, 87, 103
Zinc-blende, 90
Zoisite, 70–72, 103
Zoisite-epidote-actinolite schist, 99
Zurkirch, J., 5
Zwischengebirge, 30

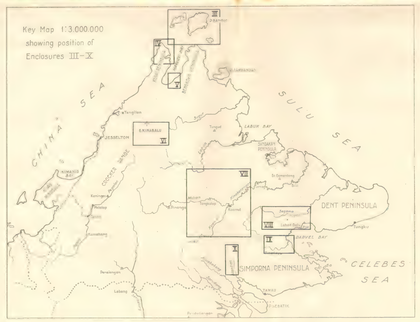
18500. Wt. P.0440. D5482. K.4. 12/51. S.P. & S. GP9-8-8.

S.O. Code No. 88-332*

GEOLOGICAL MAP OF THE COLONY OF NORTH BORNEO

COMPILED FROM REPORTS MENTIONED IN THE BIBLIOGRAPHY

SCALE 1:500.000



LEGEND

QUATERNARY

Al — Coral Reefs
Alluvial plains, fluviatile terraces, lacustrine beds, sandy marine platforms, dunes and coastal swamps.

TERTIARY SEDIMENTS (for details see Tables I and II)

Ts — Plio-Pleistocene Toppoi beds, in reef-facies: loosely cemented and brecciated reef limestones, sandstones, sands, light grey sandy/marly clays with foraminifera, gastropods, lamellibranchiata, corals; transgressive upon pre-Tertiary in Balambangan Island, disconformable (?) upon Ganduman beds in Dent Peninsula.

Tu — Pliocene Ganduman beds, in paralic facies: mainly carbonaceous clays with fossil resin and lignite seams; intercalations of foraminiferal sandy/marly clay; siliceous concretions. Marnao beds, in marine shallow-water facies: medium- to coarse-grained limonitic sands and sandstones with transitions into conglomerates; sandy/marly and carbonaceous clays; local disconformity.

Tm-t — Miocene (Miocene) Bongaya beds, in paralic to reef-facies: well bedded sandstones with plant remains and limonitic concretions, seams of glance coal; near the base coral limestones with Miogypsina, Nephrolepidina; thin basal conglomerate; transgressive upon pre-Tertiary or unconformable upon Sugut beds; series tuffaceous in eastern N. Borneo.

To1-4 — (Aquitanian) Sugut beds, in marine littoral facies: badly bedded grey to light blue, gritty quartzitic micaceous sandstones; in the lower part alternating with grey, blue, sometimes red and green shales; Eulepidina limestones; local basal conglomerate; series transgressive upon pre-Tertiary in the E., NE. and S. of N. Borneo; in volcanic facies in Dent and Simporna Peninsulas.

T(a)-b — (Eocene) Kulapis beds (in the NE. and E. of N. Borneo), in semi-arid epicontinental facies: grey, chocolate and red-brown gritty sandstones with interbedded red-brown or green shales; many salt-seeps; series in reef-facies in the N.; transgressive upon pre-Tertiary.
Kalabakang shales (in the SE. of N. Borneo, age uncertain); grey crumbling sandy shales with sandstone intercalations and calcareous concretions; bedding poor and obscured by cleavage and joint planes.

T — Undivided Tertiary (predom. Te), comprehensive thick series (mainly in western N. Borneo), in marine littoral facies: predom. grey sandstones and shales; characteristic red and green shales; rarely limestones of Te and Tb age.

TERTIARY IGNEOUS ROCKS

Py — Pyroclastic rocks: (Simporna area) andesitic conglomerates, agglomerates, tuff-breccias, tuffs and tuffites (predom. of Te age).

V — Effusive rocks: (Simporna area) andesites, dacites and basalts.

Pi — Plutonic rocks: (Mt. Kinabalan), quartz-monzonites, granodiorites and related minor intrusions and extrusions.

PRE-TERTIARY

D — Darau Formation: association of radiolarian cherts with ophiolitic rocks (serpentine, gabbro, spilite, diabase, doierite, basalt, tuff-breccia and tuff) and with contact-metasomatic rocks (adinole, spilosite, schalstein, ophicalcite ; also quartzites, sandstones, grey and variegated shales and slates, marls and limestones; formation strongly folded, contorted, often brecciated and imbricated.

Sl — Slate formation: alterations of sandstone, graywacke and dark shale, often metamorphosed to quartzite, blackish clay-slate, silky slate and phyllite; characteristic net-work of quartz veinlets.

Cr — Crystalline Schists: amphibolite, eclogite, gneiss and schists and associated intrusive quartz-diorite and diorite.

Summit with height in metres
Astronomic station
Salt water
Gas Gas inflammable
Oil seepage
Mud volcano idem, with several mudcones
Well, abandoned
Anticlinal axis
Synclinal axis
Fault
Dips: ± Horizontal
1°–9°
10°–29°
30°–49°
50°–69°
70°–89°
Vertical
Foraminiferal rock of Te1-f, age

Printed in the Hague by N.V. de Bataafsche Petroleum Mij.
Royal Dutch/Shell Group

STRUCTURAL MAP OF NORTH BORNEO AND ADJACENT PHILIPPINE ISLANDS

Scale 1 : 2.500.000

LEGEND

- Te_5-f and younger
- Tertiary Igneous (Te in Nth Borneo)
- T(a)-b-e_4, undivided Tertiary outside North Borneo
- Pre-Tertiary
- Zone of mud-volcanoes (North Borneo)
- Trend of Tertiary structures

SOUTH CHINA SEA

SULU SEA

CELEBES SEA

BORNEO

PALAWAN

PANAY

SAMAR

LEYTE

CEBU

NEGROS

BOHOL

MINDANAO

SULU ARCHIPELAGO

CAGAYAN SULU

BASILAN

JOLO

TAWI-TAWI

SIBUTU

TALAUD

SANGIHE

MANADO

CELEBES

BALAMBANGAN

BANGGI

KUDAT PENINSULA

MARUDU BAY

BENGKOKA PENINSULA

P. MANGALUM

KINABALU

LABUK BAY

SANDAKAN

CROCKER RANGE

TRUSMADI

KLIAS PENINSULA

LABUAN

BRUNEI BAY

S. Kinabatangan

S. Segama

DARVEL BAY

S. Kuamut

S. Tawau

PENINSULA

SIMPORNA PENINSULA

PGAYA

MIRI

PENGIRANGAN

TAWAU

SEBATIK

S. Sembakong

S. Sesayap

TARAKAN

S. Kayan

S. Kayan

S. Kapuas

Danau Sentarum

S. Mahakam

S. Barito

S. Pitoe

S. Mahakam

Printed in the Hague by N.V. de Bataafsche Petroleum Mij.
Royal Dutch/Shell Group

Geological Sketch Map of BALAMBANGAN, BANGGI and MANAWALI ISLANDS

Compiled from Geological Maps by W. HOTZ (1914) and W. F. SCHNEEBERGER (1935)
Petrographical determinations by M. REINHARD, palaeontological determinations by L. RUTTEN, I. W. van der VLERK and M. REICHEL

Scale 1:100000

0 1 2 3 4 5 km

117°

117° 20'

7° 20'

7°

H.62,154 marl, coral-lst. Plioc.-Quat.
Tg. Limpiang
Tg. Timohing
P. BALAMBANGAN
Lok Simamak
Tg. Siagut
Tg. Butut
Tg. Semprlok
S. Dampar
S. Sukerimit
H.61 diabase
Ba.177 lst. Tf
Ba.228 lst. Tf1-2
Batu Lingin
P. BUTAN
Lok Simpol
Ba.227 lst. Tf
H.151,152 lst. Tf
Ba.164 lst. Te5-f2
Ba.161 lst. Te3-5
Ba.167 lst. Tf
H.58 lst. Te4-5
H.59 analcite-diabase
Tg. Lingkobong
Ba.162 lst. Te5
Ba.220 lst. Tf
Ba.165a lst. Te5-f
Ba.165 lst. Te2-5
H.153 lst. breccia Tf

H.63,64 serpentine
H.65 red clay
H.54 sst.
H.67, 66 uralite-diabase
H.53 sst.
Tg. Menyangit
572m
Gg. Sinambong
Pitangyu
H.48 Leuco-gabbro
H.52 chert
H.51 diabase
H.50 rad. foram. lst. Mesoz.-Tert.
H.157 limestone-breccia Te
H.60 manganese ore sand
H.49 diabase
H.56 porphyritic tuff-breccia
H.55 serpentine
H.57 amphibolite
H.160 lst. Te
H.43,44 spilite
H.47 conglomerate
H.19 basalt
H.162 lst. Ta-b
H.161 lst. Ta-b, N.2157 lst. Ta-b
H.17,18 silicif. cryst. lst.
H.45 lst. Te5-f2
H.46 spilite
H.2 lst. Tf
N.2670 lst. Tf
N.2110 lst. Tf
H.6 rad. chert
H.5 lst. Ta-b
G.2108 lst. Ta-b
Bt. Timbang Dayang
451m
Pankalan
Kabongi
Limbuk
Bengkirit
328m
P. BANGGI
H.72 diabase
H.73 ferruginous slaty marl
H.68 amphibolite
G.2320-21 lst. Tb
H.70 chert
H.71 limestone Te3-5
P. BAHAYAN
H.69 serpentine breccia with calcareous cement
Bitara
226m
Sibaubang
H.9 sst.
Tg. Butan
P. GUHUAN
P. KAHAM KAMMAN
P. MALUNDANGAN BESAR
H.8 serpentine
P. MALUNDANGAN KECHIL
P. BATAWAN
H.7,7a rad. Foram. marly lst. Cret.-T
H.10,11 rad. chert-breccia
P. TAGAYAWAN
H.15 tuffaceous clay
Pitangyu
H.12,13 silicified spilite
H.14 sandstone
H.156 limestone Ta-b
P. RUBY
H.16 conglomerate
P. LATOAN
H.39 serpentine
H.36,37 rad. chert H.38 pyrolusite
H.158 limestone Te2-5 (+b?)
Manipang
P. BANKAWAN
P. SUNGOR
H.40 spilite
Sabur
H.41 limestone
H.42 calcif. silicif. serpentine
P. BIANGAN
Lok Sabur
I.19 lst. Tb
P. MODOM
P. PENUKARAN
H.155 lst. Te (+b?)
I.14 lmy sst Te2-3
H.163 lst. breccia Te
H.1 lst. Tf
P. KOBOG OR BALAK
P. PEGASAN
I.15 lst. Te5-f2
M.11 lst. Tfe
I.13 lst. Te1-5
G.2090 lst. Te4-5
Tg. Sibaung
P. PATANUNAN
I.1,2 lst. Tf
G.2085 lst. Te4
H.4 dolerite
H.3 phyllite
S.157 lst. Tf
P. MERIANGIN BESAR
S.50,51 lst. Tf
P. MERIANGIN KECHIL

H.27 sandstone
P. TANJONG
H.20 lherzolite
H.33 bronzitite
H.34 brecciated dunite
H.35 calcareous chert
P. MATI
H.26 chlorite-schist
H.29 rad. chert
P. MANAWALI
H.21 serpentine-breccia
H.22 limestone T.f.
H.25 dunite
H.26 bronzitite
H.24 chromite
H.23 dunite
H.30 epidote-hornblende-schist
H.31 rad. chert
H.32 bronzitite

H = samples collection Hotz
Ba, G, I, N, S = samples collection Schneeberger

LEGEND

QUATERNARY		coastal swamps sand terraces and sandy beaches
PLIO-PLEISTOCENE		coral limestones, marls and coarse sands, full of fossil debris, Timohing series
TERTIARY a+b,e,f		foraminiferal limestones and calcareous sandstones
CRETACEOUS +PALEOCENE		Danau Formation radiolarian cherts and marly limestones associated with ophiolites; incl. sandstones of unknown age (Cretaceous and/or Tertiary)
PRE-CRETACEOUS		crystalline schists

Fault
Dips: ± Horizontal
1° - 9°
10° - 29°
30° - 49°
50° - 69°
70° - 89°
Vertical

3914-PO440-5482-500-9/60 (Te.P.)

N.&W.20.000 | W.10.000 | ZERO | N.20.000

GEOLOGICAL MAP OF THE NORTHERN PART OF THE KUDAT PENINSULA

COMPILED FROM SURVEYS MADE BY G. NIETHAMMER (1913) AND W.F. SCHNEEBERGER (1935)

PETROGRAPHICAL DETERMINATION OF THE ROCK SAMPLES BY M. REINHARD, PALAEONTOLOGICAL DETERMINATIONS BY I.M. v/d VLERK

SCALE 1:100000

0 1 2 3 4 5 km.

Nh.= samples coll. by NIETHAMMER
Rh.= " " P. van RHEDEN
M S T }= " " SCHNEEBERGER

SAMPLES Nh.9-33

Nh.9,14,15,17,18,20,24,26: *spilite*
" 10,25,27: *basalt*
" 11,16: *serpentine*
" 12,33: *diabase*
" 13: *chalcedony vein*
" 19: *granodiorite (boulder)*
" 21: *natrolite*
" 22: *quartz vein*
" 23,28,30,31: *radiol. chert*
" 29,32: *limy marl*

LEGEND

QUATERNARY — *sandy beach*; *coastal swamp*

TERTIARY pred. Te ± (a+b) — *hard, unbedded and well-jointed, dark-grey, massive, fine, gritty sandstones with big globular concretions and honey-comb structure.*

clayey, locally calcareous, well bedded, light-blue sandstones, alternating with sandy clays; lenses of glance-coal and films of coaly material, foraminiferal limestones and limestone-breccias

PRE-TERTIARY ± Paleocene — ***Danau Formation*** *association of radiolarian cherts, limy marls, globigerina limestones, calcareous shales and sandstones with tuffs, spilitic tuff-breccias, spilite, diabase, basalt, serpentine, ophicalcite, silicified and calcified igneous and sedimentary rocks spilosite and adinole; S. of Kudat Harbour also leuco-quartz-diorites. Amphibolite (N. of Kudat)*

strike and dip: 1-9° 10-29° 30-49° 50-69° 70-89° 90° ◊ oil seep

f fault ← anticline ..u.. unconformity road

Tg. Sampangmangio
S. Sekrotang
Tg. Tigapapan
S. Pei
P. Kelambu
Nh.1 Te_{2-5}
Nh.2 sst.
Nh.40 brecc. lst $Ta-b$
Nh.7 sst. with foram.
Nh.6 sst.
S.11 Te_5
Tg. Loro
Nh.4,5 Te_2
S.10 Te_{1-3}
Tg. Bangau
Nh. 9-33
Nh.34,35 brecc. lst. $Te_4, Te_{2-5}(+b)$
Bt. Loro
S. Tajau besar
Tg. Tajau
S. Bak-Bak besar
Nh.41 congl. sst. with fossils
Nh.42-43 sst. with lignite
S. Bak-Bak kechil
Nh.55 chert
Nh. 54,57-59 serpentine
Nh.53 sst. b
Nh.56 Te
Agung
Agung
Nh.44,45 amphibolite
Nh.46-48 augite-porphyrite spilitic breccia spilite
Nh.52 glob. lst.
Nh.51 $Te_4(+b)$
T. 123 $Te_4(+b)$
T. 77 Te_5
Nh.49 $Te_5(+b)$
S. Bumbum
Nh.50 calc. sst.
Rh.3-4 Te_5-f_2, $Te_{3-5}(+b)$
S.14 $Te_5(+b)$
Tg. Kapor
T.13 Te_5-ff
Rh.30 $Te_{1-4}(+b)$
Rh.8 $Te_5(+b)$
KUDAT
S. Sekuati
Nh.36 sst. with lignite
Nh.37 sst. with pyrite & marcasite
Nh.38 sst. with resin
Kudat Harbour
Nh.62-64
Nh.65-70
Nh.71-73
Nh.74-82
Nh.83-93
Nh.94-98
Nh.99-100
P. Tigasamil
Rh.16 $Te_5(+b)$
Nh.101-103
S. Tigasamil
H13 Neogene, lst.
H13a Eocene, fossilif. micro-breccia
Rutten 1925 a, p. 422
Nh.61 Te_4-f_2
Nh.60 $Te_{2-5}(+b)$
M.56 $Te_{2-5}(+b)$
M.29 $Te_{1-3}(+b)$
M.23 $Te_{1-3}(+b)$

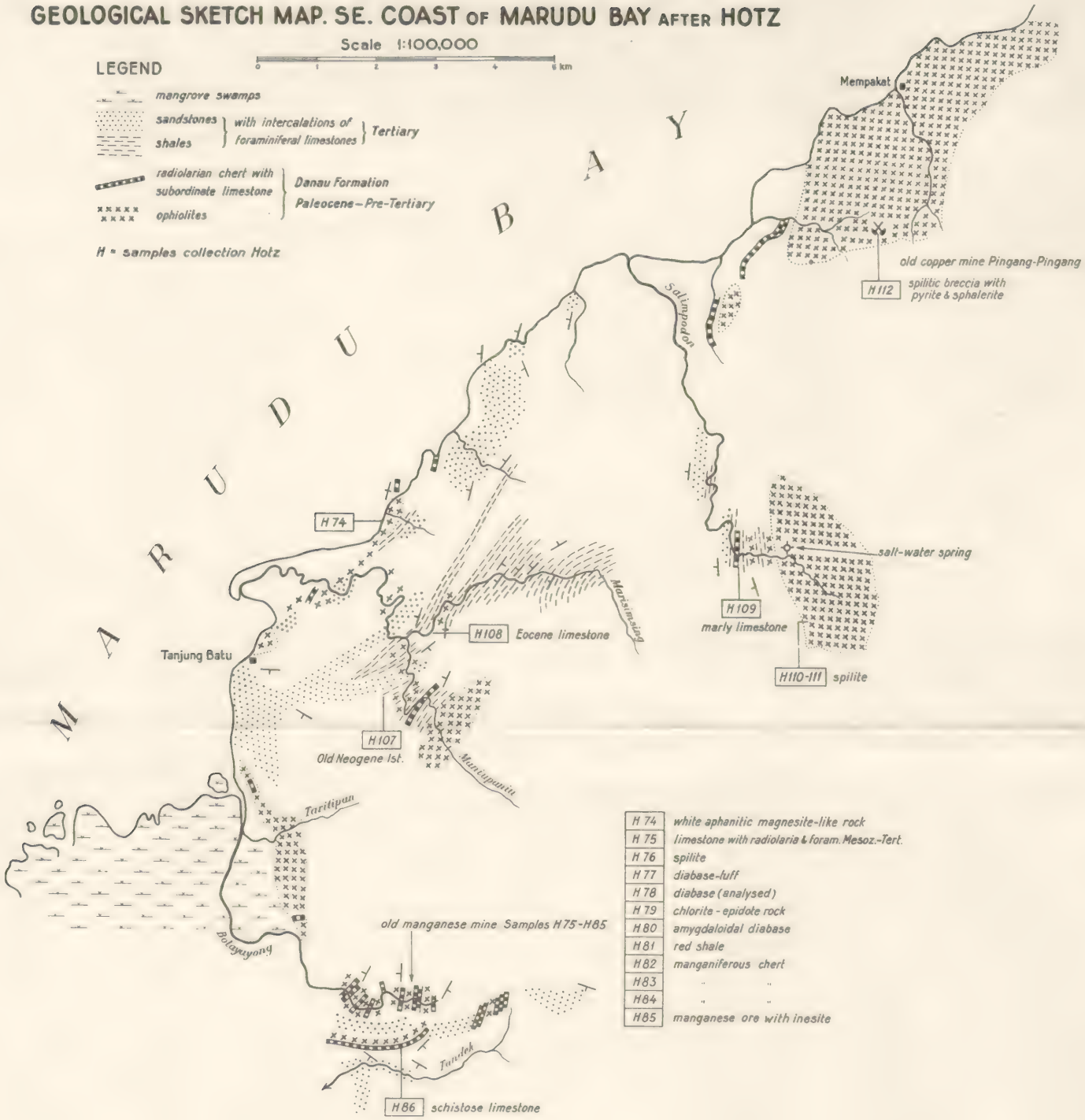
SAMPLES, Nh.62-103 (S of Kudat Harbour)

Nh.62: *prasinitic breccia*
" 63,88,89,93: *spilosite-adinole*
" 64,77: *sandstone*
" 65,66,76,84,96: *radiolarian chert*
" 67-69,87,92,98,103: *spilitic tuff-breccia*
" 70: *diabase*
" 71,100: *serpentine, silicified & calcified*
" 72: *limestone, Old Neogene (Rutten 1925)*
" 73,79: *hydrothermal quartz-calcite rock*
" 74: *calcareous phyllite*
" 75,80,82,83,90,97,101: *spilite*
" 78,81: *chert with calcite*
" 85,91,94,95,99: *leuco-quartz-diorite*
" 86,102: *ophicalcite*

N.10.000

S.10.000 | W.10.000 | ZERO

GEOLOGICAL SKETCH MAP. SE. COAST OF MARUDU BAY AFTER HOTZ



Drawing No G 10493

GEOLOGICAL MAP OF KINABALU AREA

COMPILED FROM SURVEYS BY W. HOTZ (1915) AND G. NIETHAMMER (1915) AND FROM OBSERVATIONS BY E. WENK (1937)

Scale 1:100000

0 1 2 3 4 5 6 7 8 9 10 km

Tampasuk
Kilambuan
Gg. Nungkok
Bkt. Marei Parei
Kinataki
Penataran
Gg. Kinabalu
△4100
~4096
~4086
~3920
Wk.64-67, H.137-138
Wk.69-71
H.135-136, Wk.68, 72
Wk.87-89
H.119
KOUNG
LABONG
Tohobang
H.120-122
Wk.83-86
Paka
Wk.73
H.134
H.133
H.131-132, Wk.74
H.129-130
KIAU
Wk.78-82
Kadamayan
Lobang
H.128
H.126-127
Wk.77
H.125
H.123-124
SINGARON
~1890
Gg. Sinagang
Tinompok
1250
BUNDU TUHAN
Laidan
Gg. Nonohan
~3065
Nh.460-463
Nh.458-459
Nh.453-457
Nh.464-466
Nh.450-452
Nh.449
Nh.448
Nulumat
Makadau
Nh.440
Sugut
Nh.478
Bkt. Oisapad
~825
PARANCHANGAN
Nh.474
Nh.415
Bkt. Kargan
Nh.416-417
~610
Nh.418
Nh.419
Nh.477
Nh.476
Nh.475
Langanan
Mamut
65°
H_2O
Nh.482
Nh.473
Nh.472
Bangkatan
Merali
Nh.420
Nh.421
Nh.485-487
Nh.470-471
Lohan
Nh.422
Nh.488-489
~660
Bkt. Bagahunan
TADUL
Nh.490
Nh.491
Nh.492
Nh.423
Bkt. Lunkui
~820
Nh.413-414
Nh.412
Nh.407-411
RANAU
Liwagu
Kuananan
Kenanapun
Nh.428-429
Nh.427
Nh.426
Bayan
Nh.424-425
Merali
Nh.433-437
Nh.493-497
Bawai
Nh.430-432
Bkt. Pau
~585
Kingaran
Nh.483-484
Nh.406
Nh.403-405
Kanipir
Liwagu Kuanannan

For nature of rock samples compare Appendix I

LEGEND

surveyed river
Sketched river
bridle path
△4100 trig. point, altitude in meters
~1890 mountain top, approx. altitude in meters
pass
village
cave
terrace

Dips:
0°
1 - 29°
30° - 49°
50° - 69°
70° - 89°
90°

$\times^{65°}_{H_2S}$ hot sulphur spring, temp. in centigrade

QUATERNARY — granitic blocks of rock fall; sand and gravel of alluvial terraces

TERTIARY — sandstone, variegated shale and clay; granodioritic and quartz-monzonitic igneous rocks

PRETERTIARY
Danau Form. — predom. squeezed cherts, quartzitic sandstones and shales; predom. ophiolitic rocks (spilite, diabase, gabbro, peridotite)
Slate Form. — dark, often lustrous clay slates, alternating with quartzitic sandstones and quartzites, numerous quartz veins.

Printed in the Hague by N.V. de Bataafsche Petroleum Mij
Royal Dutch/Shell Group

GEOLOGICAL SKETCH MAP OF THE MIDDLE COURSE OF THE MILIAN (KINABATANGAN) RIVER AND ITS TRIBUTARIES, INTERIOR OF THE COLONY OF N.BORNEO SHOWING DISTRIBUTION OF MINOR INTRUSIONS AND SYNCLINAL BASINS

AFTER ROOTHAAN & WENK (1936-'37)

PHOTOGEOLOGICAL INTERPRETATION BY H. BOISSEVAIN

SCALE 1 : 200000

0 2 4 6 8 10 km

COORDINATES FOR KUDAT ZERO

Copper "S. Karang" Wk 31,32,586

-150000

Antelibon

Karamuak

-170000

Bt. Tingka +580

Tangkulap

A.S. Tangkulap

Milian

Wk. 3-10 pebbles

R. 86

R 93.95 pebbles

R 85 - 87 pebbles from Kuala Tangod

Imbak

Sipoa

Bangan

S. BANGAN SYNCLINAL BASIN

-190000

-200000

Gg. Rara

Nambuatawan

Lokan

Pintasan

Kinabatangan

Daramakot

R. 94 pebbles

RW 7 Te_{2-5}

RW 6 Te_{2-5}

Bt Daramakot

RW 8 & A e-f

A.S. Kuamut

Bt Napang

S. MALUA SYNCLINAL BASIN

Malua

Marabokop

Sangitan

Kuamut

Tutuan

Wk. 1

Wk. 15 - 21 pebbles from Kuala Malog

-210000

Batu Timbang

Batu Tulis

Kastagan

Kuliatan

Kuamut

Tabaku

RW 3 Te_5-f

Wk. 12-13 pebbles

-220000

+30000 +40000 +50000 +60000 +70000

LEGEND

TERTIARY e_5-f — well bedded alternation of grey clay, shale and sandstone with coaly films, often well preserved plant remains, a few seams of glance coal, small limonitic, siliceous and calcareous concretions; fossiliferous calcareous sandstone (RW 3, Te_4-f) in S. Kuamut directly above.

unconformity — basal conglomerate (Tabaku)

TERTIARY (b)-e_4 — foraminiferal coral-limestone at top of formation (Serupi near Kuamut, Daramakot; RW 6-8, Te_{2-5}). mainly badly bedded, dull coloured, hard, fine-to medium-grained mica-sandstones with kaolinised feldspar grains, yellow-brown weathering crust; big globular concretions and convex erosional forms; in the middle part of the formation intercalated with grey, green and red shale; gradual transition into the following variegated series, separated only in S. Lokan: red-brown sandstones with intercalated layers of grey, red and green shales many salt-water seeps; this coloured series overlies the Danau Formation unconformably (Sendakan & Bengkoka Peninsulas).

basal conglomerate with quartzitic components (Tutuan, S. Kuamut)

TERTIARY — microgranodioritic igneous rocks of the Kinabalu intrusion (Gg Rara).

Age undetermined (Pre-Tertiary or younger) — Minor intrusions: basaltic dykes and small gabbroid bodies occurring within areas occupied by T(b)-e_4 sediments.

unconformity

PRE-TERTIARY (+PALEOCENE?) — Danau Formation: cherts, quartzites, sandstones and a few limestones, associated with ophiolitic rocks (gabbro, diabase, spilite, spilitic breccia, tuff, serpentine and peridotite); occasionally imbricated crystalline schists. ophiolitic gabbro and basalt.

strike and dip: 1-9° 10-29° 30-49° 50-69° 70-89° 90° fault anticline syncline

photogeological dip; disconformity; abandoned copper-mine of S. Karang

X salt-water spring; A.S. Astro-Station; Limit of navigation for small launches

ROCK SAMPLES COLL. REINHARD (1914) (RIVER PEBBLES)

R 85-87	spilite	R 86	diabase-tuff
R 88	serpentine	R 89, 95	porphyritic diabase
R 90, 93	lherzolite	R 91	uralite-gabbro
R 92	biotite-rhyodacite	R 94	troctolite

ROCK SAMPLES COLL. WENK (1936-'37)

Wk 1	basalt	Wk 3, 4	ophitic uralite-diabase
Wk 5-9	microgranodiorite	Wk 10	lherzolite
Wk 12-13	gabbro	Wk 15, 17	serpentine
Wk 16, 18-21	troctolite	RW 3, 6, 7, 8	foraminiferal limestone (see Appendix 2)
Wk 31, 32	gabbro		
Wk 586	copper ore, pyrite and chalcopyrite		

3914

GEOLOGY OF THE COLONY OF NORTH BORNEO

Enclosure VIII

GEOLOGICAL SKETCH MAP OF THE MIDDLE COURSE OF THE SEGAMA RIVER AND THE DARVEL BAY REGION (LAHAD DATU)

AFTER WANNER-STAMM (1921) AND FROM UNPUBLISHED REPORTS AND MAPS BY STAMM, JEZLER AND LEICESTER, COMPILED BY M. REINHARD

PHOTOGEOLOGY BY H. BOISSEVAIN

SCALE 1:100000

COORDINATES FOR KUDAT ZERO

LEGEND

QUATERNARY

- nipah or mangrove swamp
- freshwater marsh
- gravel, sand, loam

TERTIARY

Neogene

- reef limestone (Te_5-f), transgressive upon Pre-Tertiary (Batu Tapadong, Segama)
- conglomerates, components predom. volcanic
- andesitic tuff- and tuffite-breccias (Te_{3-a})

Tabanak beds Wanner (1921)

- sandstones and shales, alternating

Palaeogene

- sandstones, shales & marls — Darvel Bay beds Wanner (1921) — where associated with radiolarian chert and ophiolites presumably older (Paleocene-Cretaceous)

DANAU FORMATION, PRE-TERTIARY (+PALEOCENE?)

Sediments

- radiolarian cherts (St. 195 limestone with radiolaria)
- sandstones
- shales & marls

Ophiolites

- ophiolites in general, predom. gabbro
- diabase, basalt
- spilite
- ophiolitic breccia
- serpentine

CRYSTALLINE SCHISTS, of uncertain age and associated intrusives

- phyllite
- diorite, quartz-diorite, amphibolite
- hornblende-chlorite-epidote-gneiss and -schist

inflammable gas | vertical / steep / moderate dip ≠ highly disturbed strata △A.S. astro-station (Lahad Datu) \ rapid ↖ photogeological dip

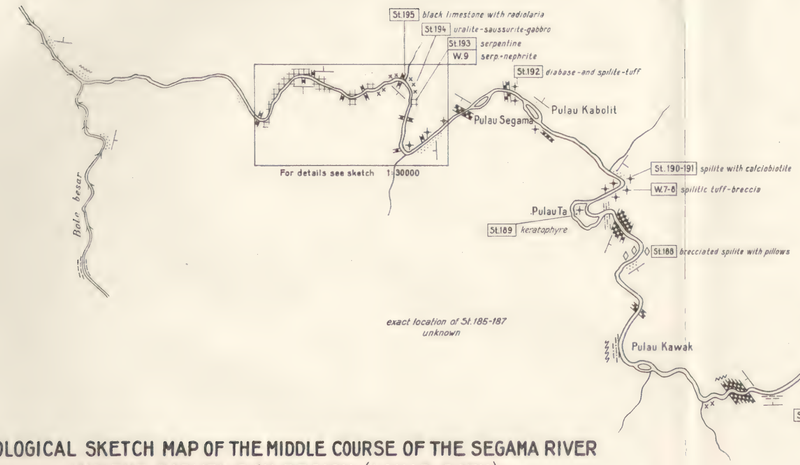
St.171 rock samples collected by Stamm

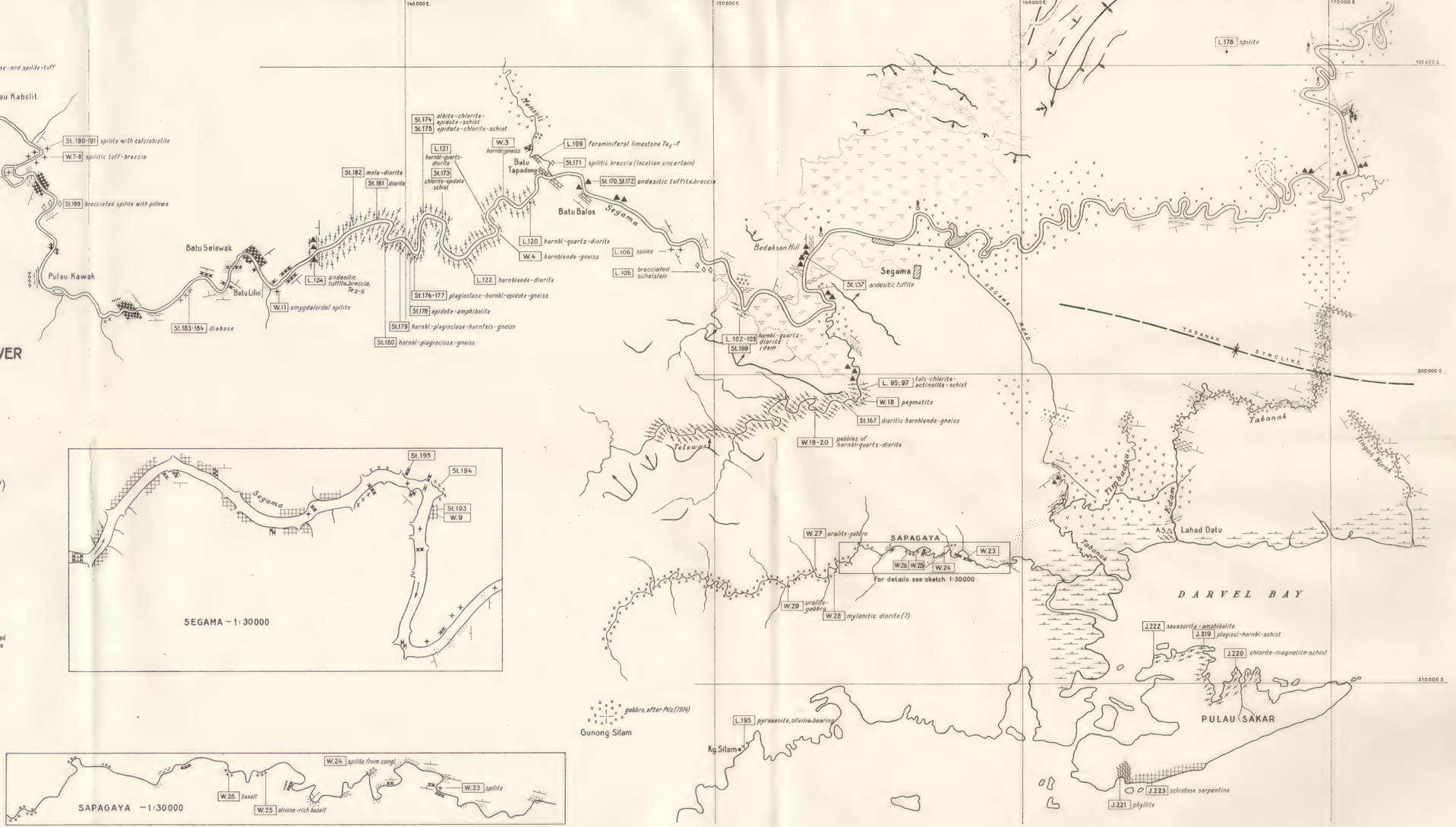
J. 219 „ „ „ „ Jezler

L. 102 „ „ „ „ Leicester

W. 26 rock samples, collected by Stamm, private collection Wanner-Stamm, detailed description by Wolfring in Wanner (1921), determinations revised by Reinhard

Batu = rock Gunong = mountain Kampong = village Pulau = island





3914-P0440-5482-500-9/50 (Ty. P)

GEOLOGICAL SKETCH MAP OF THE REGION W. OF THE DARVEL BAY AFTER WANNER-STAMM (1921)

SCALE 1:100 000

0 1 2 3 4 5 km

LEGEND

QUATERNARY

gravel, sand, loam, clay

MIOCENE

andesitic tuff and tuffite

limestone

DANAU FORMATION, PRE-TERTIARY (-PALEOGENE?) incl. OLDER CRYSTALL. SCHISTS

shales, sandstones, quartzite, marls, limestones with intercalations of radiolarian cherts (R) & ophiolitic breccias

ophiolites in general, predominantly gabbros, crystalline schists

basalt, spilite, serpentine

moderate dip, steep dip, vertical dip

salt-water spring, rapids

J 201 rock samples collected by JEZLER

W 36 " " " " STAMM, private collection Wanner-Stamm

Detailed descriptions by Bücking in Wanner-Stamm (1921), determinations revised by REINHARD

J 202 uralite-gabbro

J 201 spilite-breccia

J 203 spilite-breccia

J 204 sandstone

J 205 andesitic tuffite

J 206 id. with foraminif.

J 207 quartzite

J 208 saussuritite

J 209 radiol. chert

J 210 spilite

J 215 actinolite-clinozoisite-schist

J 216 plag-hornbl-clinozoisite-gneiss

W 30 spilite

W 31 olivine-basalt

W 36 spilite, amygd.

W 32 basalt, vesicular

W 33 calcitic tuff

W 34 schalstein

W 35 calcitic spilite

W 37 diabase

W 38 dolerite

CROSS-SECTION

Subahan

Darvel Bay

Dadong kechil

Dadong besar

Look

Tingkayu

Nanut

Benuang

Langsuan

Madai

Gg. Piton ~ 450 M

Gg. Madai ~ 150 M

CROSS-SECTION, TINGKAYU RIVER

SCALE ~ 1:500

SW NE

g W 37a diabase f W 38 dolerite e d c b a

a fine-grained sandstone

b red & green marls, with Globigerina & small intercalations of marly limestone

c grey, crystalline limestone

d green marls with Globigerina and small Nummulites (N. baguelensis Verbeek) Alveolina, Miliola & Litholhamnium, lower Tertiary, probably Upper Eocene

e red & green hard marls

f much altered ophiolitic breccia, with intercalations of red marly limestone

g serpentine, with network of quartz & pyrite

Geological Sketch Map of BLANTIAN VALLEY

Topography from aerial photographs

Geology by M. Reinhard

(Surveyed in August 1913)

Scale ~ 1:100000

0 1 2 3 4 5 km

N

Gg. Tambuku

S N thrust plane?

cross section

R 33 amphibolite

23 Gg. Tambuku ~1060 m

△ 450 m

22

R44 dunite

R34-35 serpentine

21

20

19

270 m △

R 32 spilite

R 30-31 sandstone

R 28-29 uralitic diabase

18

Paninsau

Bang

△ 250 m

17

16

17

△ 210 m

R15 sandstone with thin layers of shale

16

R14 shale

15

14

R13 spilite

R12 brecciated sandstone

13

R11 serpentine

R10 albite-gabbro

12

R9 brecciated sandstone

11

10

R8 serpentine-chlorite-schist

9

8

R7 spilite (analysed)

7

R6 chlorite-pumpelleite vein

R5 spilite

6

R4 porphyritic diabase

R3 quartzitic sandstone

5

R2 "Flysch" sandstone

4

R1 radiolarian chert

2

3

Limit of tide

1

Limit of navigation for small launches

Alluvial with nipah-nipah

Mangrove swamp

LEGEND

TERTIARY

- sandstones
- sandstones in thick layers
- idem, with shales
- shales
- conglomerate

DANAU FORMATION, PRE-TERTIARY (+PALEOCENE ?)

- radiolarian chert
- crush-breccia of sandstones
- " " of ophiolites
- " " mixed (ophiol.+sandst.)
- diabase
- serpentine
- albite-gabbro

CRYSTALLINE SCHISTS, age uncertain

- amphibolite, resting unconformably on Danau formation
- thrust plane ?
- strongly folded strata
- rapids (Biram)

R1-R35 rock samples from outcrops, collection Reinhard

R16-27 R36-65 samples collected from loose blocks, not marked on the map

Description of outcrops

1. dark shale, strongly folded, predominant dip towards N.
2. sandstones
3. dark, crumbling shales with lenticular, calcareous concretions
4. radiolarian chert, red and blue-grey
5. hard flysch-like, grey-green and reddish, brecciated sandstones, slightly calcareous; grey, soft, well-bedded shaly sandstones and laminated dark shales with fragments of splintery green quartzitic and flysch-like red sandstone and splinters of red radiolarian chert
6. small dyke of porphyritic diabase
7. ophiolitic crush-breccia with fragments of spilite, gabbro, serpentine and veins of a chlorite-pumpellyite assemblage
8. blocks of grey quartzitic sandstone with few plant-remains
9. sheared slice of serpentine-chlorite schist
10. dark squeezed shales
11. crush-breccia; angular blocks of all sizes kneaded with light green and red shales
12. sheared lens of gneissic and crushed albite-gabbro
13. brecciated sandstones and arkose
14. green breccia with blocks of sandstone and ophiolites
15. sandstones, light-grey, calcareous, generally in slabs, intricately folded, with thin layers of shales
16. sandstones, thick-layered, predominantly white and calcareous, rarely red or green and non-calcareous, generally strongly folded
17. hard green sandstones with shaly intercalations in beds of varying thickness, strongly folded or in sheared blocks floating in dark squeezed shales
18. crush-breccia; blocks of all sizes of ophiolites (gabbro, diabase, spilite, serpentine) and of flysch-like red and green sandstones floating in a matrix of green and red coloured shales
19. serpentine, with intercalations of gabbro and peridotites
20. red and light-grey radiolarian chert
21. conglomerate with boulders of radiolarian chert
22. sandstone, quartzitic or flysch-like, with thin layers of shale, in intricate folds
23. Gunong Tambuku. The steep top part is formed by a schistose amphibolite, dipping 60°-80° NNE. and resting unconformably on a basement of red radiolarian chert and red sandstones and shales

Enclosure I

REINHARD & WENK *GEOLOGY OF THE COLONY OF NORTH BORNEO*